A Study on Movement Down Spiral Staircases

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Rapport 5533, Lund 2016
Examensarbete på brandingenjörsutbildningen

The report has been written with the support of Olsson Fire & Risk

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Title

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Report 5533

ISRN: LUTVDG/TVBB--5533--SE

Number of pages: 75 (including appendices)

Illustrations: 39

Keywords

Spiral stairs, stairways, egress, evacuation, population flow, movement speed.

Abstract

Building codes around the world give extensive guidance on how to design straight stairways, and engineering guidelines provide methods to calculate movement speed and population flow in these. Less guidance is provided for spiral stairways. By conducting experiments down spiral stairways, enough data was collected to derive equations for calculating both movement speed and population flow down spiral stairways. The correlation between the calculated values and the measured values produce near identical values with R^2-values between 0.78 and 0.85. The equations are deemed suitable to use for design purposes. The equations derived here for spiral stairways give higher values for movement speed and population flow than the corresponding equations for straight stairways. It is therefore suggested that future studies should seek to validate the equations proposed in this report by conducting more experiments to gain more data on the subject.

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Acknowledgements

I wish to thank everyone who has been involved in the process of making this report possible, and I especially wish to thank the following:

Håkan Frantzich – For his support from halfway across the world. He was always quick to respond to emails, and always had new ideas to try out when the going got tough. More importantly, he shared his experience in conducting experiments and the fact that they do not always turn out the way you intended. This experience helped brace for the changes that occurred throughout the report.

Per Olsson – For guidance in determining the subject of the report. I thought that the goal was very ambitious and that it would be very difficult to complete in time, but Per remained optimistic and inspired me to push on.

Michael Spearpoint – Acting as a local supervisor halfway across the world from Lund, it is easy to say that the report would not have been possible without him. With a wide network of connections and capability to quickly come up with new plans when plans kept falling apart, Michael remained a pillar of support throughout the thesis.

Alastair Drayton and College House – A big thank you goes out to the principal of College House for letting us use their stairways for the experiment to make the thesis possible, and their common room to feed hungry participants.

All the participants who made the experiments possible – thank you for contributing with your thoughts and movement to a field that is in need of it!

Patrik Gustafsson – Christchurch, December 2016.

Summary

Buildings and constructions are designed in such a way to allow occupants to evacuate safely in the event of a fire or other circumstances. In buildings that have floors that are above or below ground level, stairs are frequently used as an evacuation route. Around the world, buildings codes tend to prefer straight stairways to spiral stairways and do not give as much guidance on how to design these. Previous studies in the field are also mostly focused on evaluating movement on straight stairways, and there are not many studies that assess spiral stairways.

The objective of this thesis is to investigate the possibility of deriving a hydraulic equation for population flow in spiral stairways. This was made possible by conducting experiments in three different spiral stairways with the help of a total of 25 participants. A fourth stairway was used, but not for the objective of the report, as it was not of a 'classic' spiral build. The dimensions of each stairway were taken before the experiment in order to be well-prepared. The experiments were recorded using two cameras for later analysis, and the movement speed and population flow were both documented for each stairway. The area of the stairs that the participants used was also documented, and was measured on which parts of the stairs the participants put their feet during the experiments. The participants were asked to fill out a questionnaire after the experiments in order to gain subjective information regarding their experience when using the different stairways.

The result of the thesis is that it is possible to derive a hydraulic equation for population flow in spiral stairs, as well as the movement speed in these. The presented equations are similar to existing equations for movement speed and population flow in regular straight stairways, but have a few differences. When compared to the equations that are used for straight stairways, the equations presented in this report produce higher values for movement in spiral stairs. This contradicts a few previous studies that state that movement in spiral stairs is more restricted than in straight ones. It is therefore important that more studies are conducted to either confirm or deny this.

The equations assume a homogenous population density in the stairs, and produce average values for movement speed and population flow. The equations allow for a higher population density than the equations for straight stairways. This is thought to be because of the tread depth of each tread decreases towards the center. The equations are suitable to use to calculate movement speed and population flow for a population density between 1.3 and 2.9 persons/m^2, as a density outside this interval still needs to be evaluated.

The questionnaires revealed that many participants were anxious due to the variable tread depth in the different stairs. By analyzing the videos of the experiment, it is also seen that all the participants are constantly looking down at their feet. The fourth stairway was located outside, spanned three stories and was constructed with grated steel, allowing the participants to see through them. More than a third of the participants expressed feeling uneasy in this stairway, and did not like the grated steel.

This thesis has presented equations that calculate movement speed and population flows in spiral stairways that are deemed suitable for design purposes. It is suggested that more studies should be conducted to validate the equations. It is also suggested that future studies should be conducted to evaluate individual behavior on spiral stairs, and to investigate if an alternative method should be introduced to measure population density on spiral stairs.

Abbreviations

ABCB	Australian Building Codes Board
ASET	Available Safe Egress Time
BBR	Boverkets Byggregler
BSI	British Standards Institution
IFEG	International Fire Engineering Guidelines
NBC	National Building Code (Canada)
NCC	National Construction Code (Australia)
NFPA	National Fire Protection Association
NZBC	New Zealand Building Code
PBF	Plan- och Byggförordning
PBL	Plan- och Bygglagen
RSET	Required Safe Egress Time

Table of Content

1 Introduction

This thesis constitutes the final step and finalization of a Bachelor of Science in Fire Protection Engineering at Lund University, Sweden. The report aims to increase the understanding of spiral stairways and attempt to derive a hydraulic equation for population flow for them. The project is in collaboration with the company Olsson Fire & Risk and is based in Christchurch, New Zealand.

1.1 Background

Today, the population in cities is continuously growing, and more people reside in high-rise buildings than ever before. The population density in buildings has increased, which in turn has increased the demand of the number and capacity of egress routes that are required. Egress routes can take the shape of corridors, doors, stairways, elevators and more. How the routes are designed may differ depending on factors such as the occupant load of the building, if the occupants are expected to be able to make their own way out, and if the occupants are familiar with the building or not. Evacuating from ground level is in general reasonably straightforward, but evacuating from floors that are above or below ground level present a much more complicated task due to the involvement of vertical movement. In order to evacuate most buildings in larger cities, stairs are a necessary evacuation route since large numbers of people reside above ground level.

Different types of straight stairways, such as dog-leg stairs and regular straight stairs seem to be the most common stair to be used as an evacuation route, and building codes around the world give extensive guidance on how these should be designed appropriately, such as acceptable widths and the location and size of landings. See chapter 4 in this report for more information. Regular stairs can take up a large amount of space, and one approach as to limit the amount of space a stairway takes up is to design a spiral stairway instead (NAHB Research Center, 1992).

Even though spiral stairways are quite space-efficient and often used when a new exit needs to be installed in an already existing building (Frantzich, 1996), building codes tend to prefer straight stairways and offer limited guidance on the design of spiral stairways. This could be because the limited amount of research that has been conducted on the topic has found that people generally move at a slower pace in spiral stairs when compared to straight ones. Another possible reason is that the depth of each tread varies depending on which part of the tread is used because the stairs are winding around a center pillar, also called a newel. This renders the walking area closest to the newel inaccessible and hazardous. Because of this, people move at a slower pace because they concentrate and use more caution in order to avoid this area.

However, according to Templer (1992), spiral stairs are said to be quite safe, and that no more accidents occur on spirals stairs than on other types of stairs. Templer (1992) presents a study made by Kinoshita (reference unavailable) which concluded that even though 6.6 percent of the stairs that were studied were spiral stairs, only 1.3 percent of the falls occurred on them. A study conducted by Kvarnström (1977) also found that less accidents occur on spiral stairs, but also states that the consequences are more severe. However, Templer suggests that accidents that occur on spiral stairs are generally not as severe as accidents that occur on straight stairs, since the occupant will fall into the railing of the stair and stop, rather than continuing down the stair as is the case in straight stairs.

There are extensive studies regarding egress using regular stairways conducted by researchers such as Kuligowski et al. (2015), Fruin (1971) and Pauls (1987), (1980), (1984). However, fewer studies that tackle the spiral stairway and its use for egress have been published. Data from straight stairs cannot be used when designing spiral stairs, since the movement pattern in spiral stairways is significantly different to that of straight stairways, people generally walk after one another in a line (Frantzich, 1996). The few studies that have been conducted on spiral stairs have concluded that the movement speed is generally lower than that in a straight stairway (Kvarnström, 1977), resulting in a lower population flow. A lower flow capacity could easily result in queueing, which in an evacuation scenario is undesirable since the evacuees are waiting around and run a higher risk of being exposed to smoke.

However, experiments in Frantzich (1996) were conducted on narrow stairways with a width less than 1 m, and experiments in Kvarnström (1977) on stairs that had narrow newels. If the stairs had been wider, it might have been possible for people to pass each other. If the stairs had a wider newel, the angle of rotation in the stairs would have been smaller, which could have resulted in a higher movement speed and larger population flow. In a recent study conducted by Bergqvist (2015), where three different spiral stairs were evaluated, the population flow was the largest in the stair with widest newel. This result is not conclusive, however, since the other dimensions of the different stairs were not the same. The results do propose an interesting question though; in a spiral stairway, can a wider newel result in a larger population flow?

When people discuss spiral staircases, they generally have in mind one with a narrow newel, and with a width to support the movement of one person at a time. But spiral stairways are not always constructed that way. Sometimes they are wider, and sometimes they have a wider newel. How do these parameters impact the capacity of the stairway? And what other parameters play an important role in the capacity of the stair?

These are questions that need to be answered so that building codes and engineering guidelines can provide proper guidance for designing spiral stairways.

1.2 Scope and Objectives

The purpose of this thesis is to evaluate the performance of spiral stairways and to attempt to derive a hydraulic equation for population flow for them. The report will focus on a specific parameter, the newel of the spiral stairway, and how its diameter can affect not only the stairs capacity, but also how the safety of the stairway is perceived. The report will also evaluate the impact of other parameters, such as the width of the stairs and the depth of the tread. This thesis aims to:

- Identify which parameters play an important role during egress using spiral stairways.
- Propose which parameters that can potentially be used to derive a hydraulic equation for flow for spiral stairways.
- Evaluate if a wider newel will decrease the differences between a regular stairway and a spiral stairway.
- Determine what more needs to be done to fully derive a hydraulic equation.

The following questions should be answered:

- Can a hydraulic equation be derived for spiral stairways?
- Which parameters play an important role in determining movement speed and population flow in spiral stairways?

1.3 Methodology

To achieve the objectives of this report, a combination of an experimental approach and a qualitative approach will be used. Quantitative data regarding the impact of different variables on population flow in the stairway are collected from experiments, and qualitative data is collected from the participants in the experiments. The qualitative data plays an important role in understanding the perceived impact of the different parameters and the subjective experience of each subject regarding the movement down the stairs.

In the initial stages of the thesis a brief study of previous studies was conducted to gain an overview of the amount of knowledge surrounding both straight and spiral stairways. To find as much information as possible, the search included the use of Google, different library databases and engineering databases. Databases that were used include:

- Lund University Library's search engine (Lovisa, LUB)
- Luleå University Library's search engine
- University of Edinburgh Library's search engine
- Civil Engineering database (ASCE)
- University of Canterbury's search engine and library

Keywords such as evacuation, egress, stairs, spiral stairs, helical stairs, flow were used. The study incorporated not only articles and research papers but also engineering guidelines such as the SFPE Handbook (NFPA, 2008). To gain further insight on the topic building and construction codes from different countries were reviewed. The countries that are included are Sweden, Australia, New Zealand, United Kingdom, Canada and the USA.

1.4 Limitations

The report has a few limitations to consider, some of which include:

- During the experiments, only movement down the stairs is to be evaluated, as opposed to movement up the stairs.
- The report will be limited by the number and configuration of the stairways that will be available for the experiments.
- The report will be limited by the number of participants that agreed to take part in the experiments.
- The participants that are chosen to participate in the experiments are expected to be able to make their way down the stairs without aid.

The final limitation is time, which combined with the available stairway restricted the number of parameters that can be evaluated in this report.

2 Previous studies on evacuation and crowd dynamics

There have previously been numerous studies that have investigated and analyzed population flows, movement speeds and human interaction on both horizontal platforms as well as stairs. Some of these studies are listed and summarized below.

It is important to note, however, that global demographics have undergone significant changes in recent decades, especially in Western countries, as both heart disease, obesity and associated factors have increased (Proulx, 2008). Because of this, data from older studies may no longer be representative of the current or future population, and results from Spearpoint & Maclennan (2012) suggest, with the help of modelling, that when comparing data from Canada in 1971 with a future New Zealand in 2031, total evacuation times may increase by 20%

2.1 Kuligowski

Kuligowski (2015) conducted a recent study on people's movement in stairways. The study was influenced by a few features of previous work on the subject, the first being the fact that most data on the subject is several decades old, and it is thought that the current population would be slower than what is presented in the old data. Secondly, older studies have not been conducted in buildings higher than 21 stories, which made higher buildings an interest for this study. The third and final feature is that old studies produce only mean values or a range of values. Kuligowski set out to provide more detailed data that can be used in newer, more sophisticated egress models.

The study included 5244 participants and 14 different buildings were used, ranging from 6 to 62 stories in height. The participants included people with movement disabilities and people who are in need of assistance during evacuation.

The most interesting find from the study is that the flow of the occupants in the stairways were mainly dependent on the total number of occupants evacuating and the height of the building that was being evacuated. The following equation for flow was produced in the study:

$$F_{ave} = 0.42(\frac{P_{total}}{D_{exit}})^{\frac{1}{3}} \qquad \text{[Equation 1]}$$

F_{ave} = mean flow [persons/s]

P_{total} = total number of people using the stairs [-]

D_{exit} = maximum distance travelled by the people using the stairs [m]

The fact that it was found that the width of the stairway did not have an impact on population flow is surprising as most previous work on the subject has found that the width directly impacts the population flow.

2.2 Togawa

Togawa (1955) conducted a variety of different studies in Tokyo on how the movement speed varies for people in different environments. The studies are quite useful as they cover peoples' movement speed up and down stairs, through door openings, in warehouses, corridors, theatres and more. Included in his findings is that the inclination of the stairs directly influences the movement speed in the stairs, and that the movement speed in the stairs depend on the width of the stairs. However, the latter is only true if there is a group of people using the stairs, as there was no notable difference when a person used the stairs by themselves.

Togawa derived an expression for the total evacuation time with regard to population flow through a connection, e.g a stairway, plus the time it takes for an individual to get from one place in the room to the connection. See equation below.

$$T = \frac{N}{B \cdot F_s} + \frac{L}{v}$$ [Equation 2]

T = total evacuation time [s]

N = number of people [-]

B = width of evacuation route [m]

F_s = population flow [$m^{-1}s^{-1}$]

L = distance to exit [m]

v = movement speed [$\frac{m}{s}$]

The study conducted by Togawa has one limitation which is that most of the people that were being studied were commuters in Tokyo; they had knowledge of where they were going and how they were getting there since they do it every day. This makes it difficult to apply these studies to an egress situation, where people are not expected to know very much about their surroundings.

2.3 Fruin

Fruin (1971) conducted an extensive study in New York with the intent to investigate how movement speed and population flow varies in stairs, corridors and through door openings, and how the population density affected these. The interesting part about the experiments that Fruin conducted is that he studied the behavior of the population and how it was affected by queueing and conflicts.

The study was carried out in bus and train terminals and on regular streets with the intention to collect data that could be used for design purposes, and involved around 1000 persons. The people in the study were mainly commuters, just like in the study by Togawa. The data is valid for movement during normal conditions but is used frequently to design evacuation routes.

An important note made by Fruin is that the physical dimensions of the human body impact the practicality of moving in stairways and walkways. He proposes the elliptical body template which takes into account the natural sway a body has when walking or standing still. Fruin also brings up the perception of personal space and how it may impact movement characteristics.

Fruin presents a Level-of-Service Concept in which different levels of population density impacts the characteristics of pedestrian movement on walkways, stairways and in queues. The six different levels that are presented, A to F, describe different intervals of population density and population flow, and present the circumstances in which movement can occur, see Table 1. Fruin presents the population density as square meter per person and the population flow as persons per meter width of connection, per second.

Table 1. Levels-of-Service for stairways.

Level-of-Service	**A**	**B**	**C**	**D**	**E**	**F**
Density [m^2/p]	≥ 3.2	2.3-3.2	1.4-2.3	0.9-1.4	0.5-0.9	≤ 0.5
Flow [p/(m*s)]	≤ 0.4	0.4-0.6	0.6-0.8	0.8-1.1	1.1-1.4	Variable, up to 1.4

Service levels up to C are considered to allow for comfortable movement to occur. Service level F entails extremely high density, and is not recommended to use for design purposes.

Fruin's observations on stairs include that the population flow depends more on the layout of the stairway compared to the population density. This is due to that people more seldom pass each other while walking in stairs in comparison to corridors, where it was noted that the population density plays a larger role on determining flows. The result is that movement speed in stairways is often regulated by the slower-moving individuals.

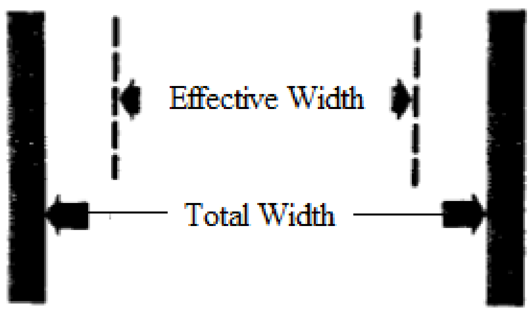
2.4 Pauls

Pauls (1980), (1984), (1987) has conducted numerous studies regarding the evacuation phenomenon. He has published many more studies than the ones cited in this report, but these three summarize some of his most important work. He has studied evacuation scenarios in high rise office buildings, investigating movement speed and the behavior of the people evacuating. Extensive studies were conducted on different office populations and included individuals who had minor physical disabilities, which implies that the results are appropriate to use when designing evacuation routes.

Regarding stair safety, Pauls found that the most common reason why accidents occur on stairs is when the occupant misjudges where the tread edge is, or misplaces their foot on the tread. The reasons this occurs is when the occupant is not able to properly see the edge of the tread, and that the tread is not large enough to place their foot comfortably.

The most commonly used rule used for designing the treads and risers in a stair is expressed as *twice the riser height plus the tread depth* (2R+T), and that it should be in the interval between 610 mm and 635 mm. The rule was developed in France centuries ago, and Pauls debates that *"the rule was meant to be applied to stairs with a moderate pitch and not to stairs as steep as many found today"* (Pauls, 1984, s. 33). He also notes that the rule uses the pre-evolutionary inch which was larger than the inch used today, adding to the reasons that the rule should not be used today.

A major observation from Pauls studies is the introduction of the effective width method (Pauls, 1984). When people use stairs, they do not fully utilize the entire width due to that they keep some distance between themselves and the wall and the fact that they do not walk in a completely straight line due to the lateral body-sway of individuals. The effective width of a stair does not include the areas closest to the sides of the stair that are generally unused. The results are based on observations made from 58 different building evacuations. Other findings include that the mean flow is a linear function of the stair width, and not a step function which had previously been assumed in models using lanes of movement. Pauls concludes that the effective width rather than the actual width should be used when calculating the population flow on stairs. The effective width in stairs are calculated as approximately:



- 150 mm from each wall, and
- 90 mm from the middle of the handrail

Pauls also concluded that slower moving individuals were overtaken in stairs and thus, no clear decrease in the total population flow was notable. Combined with Fruin's findings this indicates

Figure 1. Illustration of the effective width.

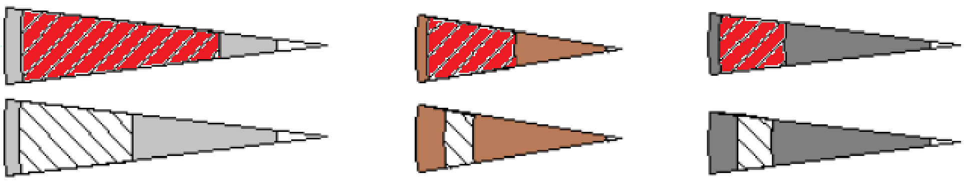
that people do pass each other more often when in an evacuation situation compared to a normal situation.

2.5 Bergqvist

Bergqvist studied how different dimensions of spiral stairways impact the evacuation process (Bergqvist, 2015). The study incorporated three different spiral stairs of varying dimensions and included one test where the participants made their way down the stairs at a regular pace, and one test where they made their way down at a ‘hurried’ pace.

The documented population flow for the different stairs differed between 0,5 and 0,6 persons per second when the participants were moving at a regular pace, and flows between 0,85 and 1,29 persons per second were measured when they were moving at a hurried pace.

Findings include that if the stairs are wide enough it is possible to pass slower moving individuals. Another interesting result from the study is that the actual walking area was at least twice the value of the theoretical walking area in all three of the stairways. The walking area of the stairs are described as the area on which the participants put their feet on while descending. Bergqvist states that the walking area for spiral stairs is determined in the same way as for straight stairs; a tread depth of at least 25 cm, measured 15 cm from the edge of the stair. However, after looking up the reference provided by Bergqvist, the author did not find this information. The actual walking area is marked in red and the theoretical walking area is marked in white in Figure 2.



However, in her study, Bergqvist encouraged the participants in the study to pass one another in the second test. This might have imposed the behavior of using a narrower part of the tread which

Figure 2. Actual walking area (red) and theoretical walking area (white).

might not be the case under normal circumstances.

2.6 Kvarnström

Kvarnström (1977) studied the use of stairs in buildings during the 1970s and 1980s. The studies also incorporated the use of stairs during egress and Kvarnström compiled a large amount of data on movement speed in different stairs.

Kvarnström states that the tread depth for stairs should be within the interval 25 to 30 cm, and that the riser height should be between 15 to 20 cm, whereas 17-18 cm is considered an ideal height for the riser. Using the French method described by Pauls, this gives a gait of 590-660 mm. He also noted that a tread measuring 23 cm is accepted for narrow spiral stairways.

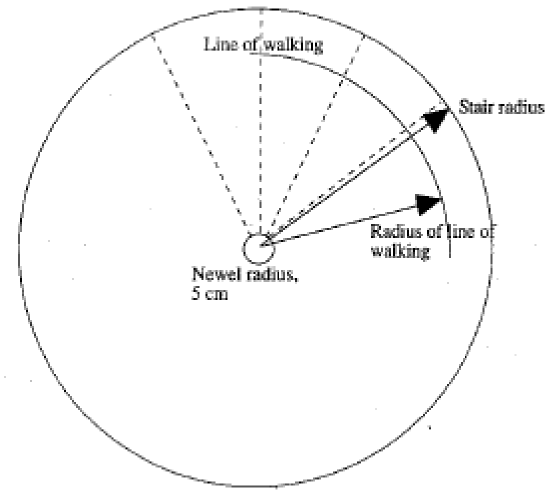
For spiral stairways Kvarnström measured population flows between 0,50 and 0,67 persons per second for stairs with a width of 0,67 and 1,10 m.

The study concludes that wide floor-to-floor stairs are the fastest stairs to use in an evacuation, and that the same type of stairs, but with regularly occurring platforms are the safest. Accidents occur less frequently in spiral stairways due to the lower movement speed, but the consequences are also more severe.

2.7 Frantzich

Håkan Frantzich (1996) carried out egress exercises in Sweden in the 1990s. The spiral stairways that were used in the experiments had a width of 0,65 and 0,85 m and a newel with a radius of 5 cm, see Figure 3. Frantzich suggests that one reason that the movement speed in spiral stairways is lower than in regular straight stairways is that the incline in the line of walking is greater. The stairs mentioned above had an incline of 43° and 45°.

The experiments resulted in an average walking velocity of 0,5 m/s in the narrow stairway and 0,55 m/s in the wider. An interesting observation is that an increased population density had no effect on the movement speed. The population flow in both stairs was measured to 0,55 persons



per second, but the wider stair was considered easier to use due that it was wider and that the line of walking was perceived as straighter when compared to the narrow stairs.

Figure 3. Geometry of one set of stairs used by Frantzich. (Frantzich, 1996)

2.8 Predtetschenski and Milinski

Predtetschenski and Milinski (1971) conducted studies on the movement speed on both horizontal surfaces as well as stairs. The most notable difference in their work is the way they define the population density. Predtetschenski and Milinski define the density as the relation between the horizontally projected area of people in a connection and the total area of that connection, resulting in a dimensionless variable, see equation below.

$$D_{pm} = \frac{f \cdot n}{l \cdot b} \qquad \text{[Equation 3]}$$

D_{pm}= population density [-]

f = horizontally projected area per person [m^2]

n = number of people in the room [-]

$l \times b$ = area of the room [m^2]

The two researchers measured the horizontal area different people occupy depending on gender and age. This information makes it possible to calculate the density in most scenarios.

The studies conducted by Predtetschenski and Milinski resulted in a vast amount of data that helped them statistically derive an equation for measuring movement speed on a horizontal plane. The equation is dependent on the density, D_{pm}, and can be altered to be used for different connections such as corridors, door openings and movement up and down stairs, see equations below.

$$v = 112D_{pm}^4 - 380D_{pm}^3 + 434D_{pm}^2 - 217D_{pm} + 57 \qquad \text{[m/min]}$$

$$v_{door} = v \cdot m_{door} \qquad \text{[m/min]}$$

$$m_{door} = 1{,}17 + 0{,}13\sin(6{,}03D_{pm} - 0{,}12)$$

$$v_{down} = v \cdot m_{down} \qquad \text{[m/min]}$$

$$m_{down} = 0{,}775 + 0{,}44e^{-0{,}39D_{pm}}\sin(5{,}61D_{pm} + 0{,}224)$$

$$v_{up} = v \cdot m_{up} \qquad \text{[m/min]}$$

$$m_{up} = 0{,}785 + 0{,}09e^{-3{,}45D_{pm}}\sin(15{,}7D_{pm}) \qquad 0 < D_{pm} < 0{,}60$$

$$m_{up} = 0{,}785 - 0{,}10\sin(7{,}85D_{pm} + 1{,}57) \qquad 0{,}61 < D_{pm} < 0{,}92$$

The specified speeds are calculated for normal situations, but Predtetschenski and Milinski have used similar coefficients as above that can be used for egress situations. These coefficients are purely theoretical and there are no experiments in their studies that support them.

2.9 Thompson

Peter Thompson (1994) critically reviewed many past studies on crowd movement and crowd dynamics. He found that all previous studies had only analyzed crowd movement based on general parameters such as a total flow rate and an average movement speed in a crowd, and that there is a lack of studies that analyze the movement of individuals in a crowd.

Thompson introduced a new parameter, the inter-person distance, and comments that the movement of individuals is largely affected by other individuals around them (Thompson, 1994). The inter-person distance is measured from the center of one body to the center of another body. The distance can be translated into a density measurement using geometrical calculations to calculate the area used by an individual:

$A = 0.87d^2$

$D = \frac{1\,person}{A} = \frac{1}{0.87d^2}$

$d = \sqrt{\frac{1}{0.87D}}$ [Equation 4]

$A =$ area [m^2]

$D =$ density [1 person/m^2]

$d =$ inter-person distance [m]

The equations make it possible to translate data for crowd motion (movement speed, population flow) into figures that relate to the inter-person distance for individuals in a crowd.

2.10 Larusdottir and Dederichs

A study conducted by Larusdottir and Dederichs (2012) looked to evaluate the movement characteristics of children in the event of an evacuation. Characteristics such as population flow through doorways and movement speed were documented for children up to six years old. A total number of 66 children, aged three to six, participated in evacuation using three different spiral stairs.

The movement speed of the children was measured at a density where they could move independently, and the average speed in each stairway varied between 0,13-0,58 m/s. Findings include that the movement speed does not depend on the width of the stairs, since the children moved in a single file in each case. Another finding is that the familiarity and design of the stairway played a big role when determining the children's movement speed; when using a stair that they had not used before, some of the children came to a complete stop to take in the new surroundings.

2.11 Najmanova and Ronchi

Najmanova and Ronchi (2017) recently conducted a study similar to Larusdottir and Dederichs, where both the movement and behavior of pre-school children were evaluated and documented. The study consisted of two evacuation drills in the same school, located in Prague. Movement characteristics were documented on horizontal planes, internal and external straight stairways, and external spiral stairways. A total of 188 children, aged between three and six years old, participated in the study.

Results from the study include a confirmation of the observation made by Larusdottir and Dederichs, that the movement of children depends on the familiarity of the stairway and environment. The movement speed of children evacuation using the spiral stairways varied between 0,38-0.87 m/s.

2.11 Hoskins

Hoskins (2011) conducted a wide review of past studies looking at flow dynamics in stairs in order to develop a theory underlying people moving down stairs. The study included reviews of existing equations and parameters that impact movement in stairs.

Findings include that individual behavior plays an important role when determining movement down stairs. New parameters are introduced and evaluated by Hoskins, including the use of flow units; small groups of people descending the stairs at the same pace. Flow units move at the speed of the 'first person' in them, another parameter introduced in the study. Hoskins states that conducting research to better understand the human movement principles will pave the way to conduct experiments that focus on how people actually use stairs, which in turn can help improve the development of reliable models.

Hoskins argues that assuming a homogenous density for a crowd is not conservative, and that existing equations do not take into account that there are individuals in a crowd that move at a much slower pace. He further states that when calculating speed and flow for a stairway that the slowest individuals should be prioritized to ensure that everyone can evacuate in time.

2.12 Summary of data

Table 2 presents some of the documented data for flow down spiral stairs. The depth of the tread is as measured 300 mm from the outer edge of the stair, except for Larusdottir & Dederichs (2012) study, where the tread is measured 250 mm from the outer edge.

Table 2. Summary of data from past studies on spiral stairways.

	Width [mm]	Newel diameter [mm]	Riser [mm]	Tread [mm]	Population flow [p/s]	Movement speed [m/s]
Frantzich	650	50	200	210	0.55	0.50
	850	50	180/210	180	0.55	0.55
Kvarnström	670	N/A	150/193	180	0.51/0.52	N/A
	1100	N/A	150/193	290	0.67	N/A
Bergqvist	1480	550	155	330	0.58	N/A
	1000	160	170	250	0.50	N/A
	1160	380	175	260	0.56	N/A
Larusdottir & Dederichs	800	N/A	190	290	N/A	0.58
	870	N/A	190	290	N/A	0.38
	910	N/A	170	290	N/A	0.13
Najmanova & Ronchi	1200	N/A	165	420	N/A	0.53
	1200	N/A	165	420	N/A	0.59

In the studies conducted by Bergqvist and Kvarnström, the flow is calculated for the entire time spent in the stairs, from the moment the first participant entered the stairway until the final participant exited the stairway, not just past a specific point in the stairs. As a result, the documented population flow for these stairs are lower than if they had been measured at a specific point in the stairway.

3 Theory

3.1 Available design methods

There are two existing design methods that are frequently used in practice when designing evacuation routes in a new or existing building (Frantzich, 1994). The two methods are significantly different, one being based on prescriptive standards (Hagiwara & Tanaka, 1994), and the other being more analytical, using engineering based calculation methods (Frantzich, 1994).

The prescriptive method is built upon empirical judgements and previous experiences and is very useful when designing routes for conventional buildings. The designer is not required to have any knowledge regarding the evacuation process and simply uses handbooks and national building codes, where the required dimensions and walking distances are provided. As a result, this method is very cheap to use. (Frantzich, 1996)

The method does however have some drawbacks. Due to the simplicity of the method, it does not guarantee the same level of safety for all buildings (Frantzich, 1994). The method has also had different results worldwide due to the variation in different countries building codes (Hagiwara & Tanaka, 1994).

Due to the drawbacks in the previous method, an analytical method can also be used. This method is commonly used when designing evacuation routes in more complex buildings (Frantzich, 1996). In this case, the designer is required to have a certain level of knowledge of the evacuation process, human behavior and in fire engineering. The method uses engineering based calculations to compare the time it takes to evacuate a building with the time that passes until untenable conditions are reached in the building. (Frantzich, 1994)

The movement time in evacuation routes plays an important role in providing a reliable assessment and design when using the analytical method. This report will hopefully improve the level of knowledge regarding the movement phase in spiral stairways and therefore improve the reliability of the method.

3.2 The evacuation process

A person who is evacuating a burning building is constantly being faced with decisions and impulses that need to be dealt with. The impulses occur throughout the entire evacuation process, and involve everything in between becoming aware of the fire (although evacuees are not always aware that there is a fire, and act on other impulses such as an alarm) and safely manage to get out of the building. The person in question must first understand that there is a fire and later act based on this information. A new decision will be made and this process will be repeated until the person has made it out of the building. (Frantzich, En modell för dimensionering av förbindelser för utrymning utifrån funktionsbaserade krav, 1994)

The total evacuation time of an individual can be divided into the premovement time and movement time (Proulx, 2008). The premovement time is defined as the time to recognition of an event and the initial response, and the movement time is defined as the time taken until the evacuee has made it out of the building or reached a safe place. The total evacuation time is also known as the required safe egress time, or RSET (Proulx, 2008).

The available safe egress time (ASET) is the time from the ignition of a fire until the conditions in the building, or part of the building, become untenable (Proulx, 2008). To be able to safely evacuate in the event of a fire, the occupants of a building need to do so before this time.

$$RSET < ASET \qquad \text{[Equation 5]}$$

For engineering purposes, RSET can be divided into four different phases that each can be quantified (Gwynne & Rosenbaum, 2008):

$RSET = t_d + t_n + t_{p-e} + t_e$ [Equation 6]

$t_d =$ Detection phase; the time from fire ignition until the fire has been detected.

$t_n =$ Notification phase; the time from detection until occupants have been notified of the emergency.

$t_{p-e} =$ Pre-evacuation phase; the time from notification until evacuation begins.

$t_e =$ Evacuation phase; the time is takes the occupants to move to a safe place.

The detection and notification phase are in many cases the same, as they both usually involve as technical solution such as a fire alarm systems (Gwynne & Rosenbaum, 2008). The phases will differ in the case where an occupant needs to manually activate the fire alarm after discovering a fire (Proulx, 2008). Depending on the type of fire, the type of detection devices that are installed plus other factors, the detection phase can take between seconds and hours.

The pre-evacuation phase represents the behaviour and response of individuals after being notified of a fire. This phase is made up of the time it takes from becoming aware of the situation to making a decision and act accordingly. The signal from the notification phase is now identified and then interpreted which prompts an action. This action could be to move towards and exit, find out what it going on, try and fight the fire, help other people or in some cases, completely ignore the signal (Proulx, 2008). The pre-evacuation phase is in many cases longer than the other phases and it is therefore of significant importance to be able to predict it (Frantzich, 1996).

The final phase in the model is the evacuation phase. This phase revolves around the specific action to leave the building. The evacuation phase consists of the time it takes for an occupant to make his or her way out of a building, which may involve a variety of different routes depending on what type of building it is. This time can be calculated, which makes it essential to know at what speed occupants typically move when using different escape routes and the flow time through the different connections that are used (Proulx, 2008).

This report will focus on the evacuation phase, and more specifically on movement down spiral stairways.

3.3 Existing equations for movement speed and population flow

The movement speed of either a group or an individual in a group has been found to be a function of the population density (Gwynne & Rosenbaum, 2008). Important to note is that if the population density is more than 3,8 persons/m^2 it is too dense for movement to take place, and if the population density is less than 0,54 persons/m^2 the movement speed of individuals will be independent of the movement speed of the persons around them. Equation 7 has been derived under the assumption there is a linear relationship between population density and movement speed within the interval of 0,54 and 3,8 persons/m^2. The assumed maximum density of 3,8 persons/m^2 is higher than the heaviest occupant load suggestion in the NFPA 101, Life Safety Code (2006) and is therefore a conservative assumption, and the equations can also be seen as conservative.

$S = k - akD$ [Equation 7]

S = movement speed [m/s]

k = constant that is dependent on tread depth and riser height, see table 2 below [-]

a = 0,266 [-]

D = population density [persons/m^2]

The movement speed can now be used to derive the equation for specific population flow. The specific flow is measured as the population flow per meter of effective width of the stairs. The equation for the specific flow is as follows

$F_s = SD$ [Equation 8]

F_s = specific flow [persons/s/m of effective width]

Equation 7 and 8 can be combined to produce an equation where the specific flow is only dependent on the population density

$$F_s = (1 - aD)kD \quad \text{[Equation 9]}$$

Table 3. Constant values of k for Equation 6, 7, 8 and 10.

Riser [mm]	**Tread [mm]**	**k [-]**
190	255	1,00
180	280	1,08
165	305	1,16
165	330	1,23

Gwynne & Rosenbaum do not present a method on how to calculate the k-value for different stairs. However, Buchanan (2001) presents a method to calculate these:

$$k = 0.86\sqrt{\frac{G}{R}} \quad \text{[Equation 10]}$$

G = Tread depth in going [m]

R = Riser height [m]

To calculate the total population flow in a stairway, simply multiply Equation 8 with the effective width of the stairway. This can be done under the assumption that the population flow in the stairs is directly proportional to the width of the stairs.

$$F_c = (1 - aD)kDW_e \quad \text{[Equation 11]}$$

F_c = Calculated flow [persons/s]

W_e = effective width [m]

The above equations are applicable to straight stairways. No guidance or equations are available for spiral stairways.

3.4 Important parameters in movement and spiral stairs

3.4.1 Movement in crowds

There are three basic characteristics that impact movement patterns in crowds, which are population density, speed and flow (Proulx, 2008). Combined with the width of a walkway or a path, these characteristics make up the fundamental traffic equation.

$$Flow = Speed \times Density \times Width \qquad \text{[Equation 12]}$$

It is important to remember is that the speed must be measured along the slope of the stair, not the horizontal projection of the stair. Another important note is that the characteristics are dependent on each other, considering that the closer people are to one another, the slower they are able to move. Noteworthy is also that higher densities can be quite uncomfortable depending on culture and the relationship people have to those standing next to them. (Proulx, 2008)

3.4.2 Movement in spiral stairs

This section gives a brief description of parameters that are of interest regarding movement down spiral stairs. An illustration of a tread and the parameters are presented in Figure 4.

Newel diameter

The typical spiral stairway usually equipped with a newel with quite a small diameter. This renders the inside part of the stairway difficult to use, as the angle of rotation around the newel is high, and great caution must be taken. If the diameter of the newel is increased, it will result in a lower angle of rotation which could result in a smoother and greater flow down the stairway.

Riser

The height of the riser in a stairway directly impacts how many treads are needed to reach the end of the stairs. If the riser height is high, less distance needs to be travelled horizontally to make it down the stairs, and the same principle applies to if it is low, more distance will need to be covered. However, if the riser is too low or too high, it risks affecting the gait of the person using the stairs.

Kvarnström (1977) documented an increase in movement speed down a set of spiral stairs when he increased the riser height from 15 to 19 cm. The difference resulted in an increase in flow of merely 0,01 persons per second.

Tread

Similar to the riser height, the tread depth impacts the total distance that needs to be covered to make it down the stairway. The tread cannot be too shallow or it may risk a person stumbling, and it cannot be too deep or it may affect the gait of a person, causing them to take two steps on a single tread.

Important to note is that there is a correlation between the riser height and the tread depth that directly impacts the gait of an individual. Guidelines for the correlation is given as either the slope of the stairway or the French method presented as ‘2R+T’.

Width

The width of the stairway has a large impact on the population flow, and is one of the three deciding parameters in the traffic equation presented above. An interesting aspect that is dependent on the width is the possibility to pass others when moving down the stairs. Frantzich (1996) found that the width of the stairway did not impact the population flow, but the stairs that were used were both narrow at 0,65 and 0,85 m, and passing was not observed. A larger width is needed to be examined to draw further conclusions.

Handrails

The impact of having a handrail not only on the outer side of the stairway, but also on the inner side will be analyzed in the experiment. If a handrail is only installed on the outer side, it might encourage the users to move in a single file, all whilst using the handrail. But combining a wide stairway with having a handrail on the inside can hopefully make it easier to pass others on the way down. Having a handrail on the inner side of the stairs will hopefully increase the experienced stability toward the center of the stairs, thus increasing the usable width of the stairs.

Landing

A few building codes recommend a maximum height or a maximum number of treads in between landings. This is to mitigate the consequences of a potential fall in the stairs as the landing proposes a hindrance to the momentum gained in a fall down stairs. The landing can also serve as a short break in using the stairs and can also be a possibility to pass others, as this is easier to do on flat ground than on stairs.

Material

Which material the stairway is constructed of may impact the movement speed of the occupants; if the stairway is constructed of concrete it may give a more stable experience when compared to a stairway constructed using grated steel, where it is possible to see through the treads.

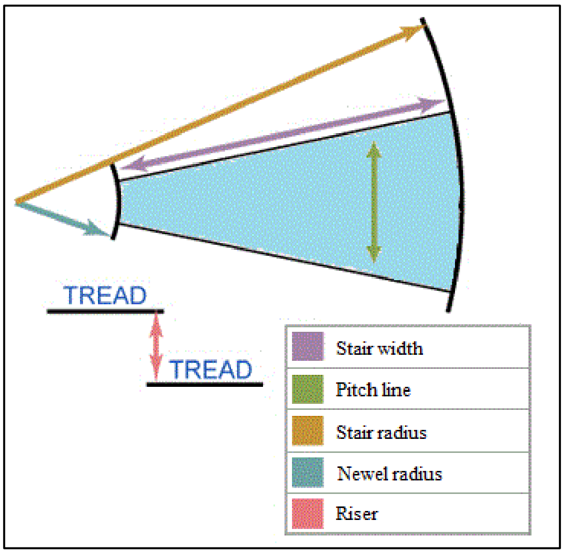


Figure 4. Parameters of a tread in spiral stairs.

3.5 Effective width and boundary layer

The effective width is described as the usable or walkable width of a route, and was first introduced by Pauls (1984). When using routes to exit a building, people tend to create a certain space between themselves and the things around them such as walls or handrails. This space is referred to as the boundary layer, and is needed to assure balance, as the human body has a slight sway to it when it moves. (Pauls, 1984)

The effective width of an evacuation route is measured as the clear width of the route minus the width of the boundary layers. The clear width is described as the entire width of the route, and is for stairs measured as the width of the treads. The boundary layer width for the different elements in a stairway is 150 mm for the wall or the side of the tread, and 90 mm for the handrail and railings. (Pauls, 1984)

3.6 Inter-person distance and population density

Population density is an important parameter when designing evacuation routes. It is one of the parameters in the fundamental traffic equation presented in chapter 2.3 and engineering guidelines such as the SFPE handbook have derived equations where both movement speed and population flows are dependent on the population density (Gwynne & Rosenbaum, 2008).

Population density in stairs can be calculated using two different methods (Hoskins, 2011). The first method simply counts the number of people per floor area. The difficulties when using this method is choosing which area to use in the calculations, as the entire area of the stairs is not used and an effective area should be determined.

The second method counts the number of empty treads between occupants in the stairs (Hoskins, 2011). Thompson (1994) discusses the inter-person distance presented in section 2.9. However, the inter person distance assumes that an individual is surrounded by others, which is not always the case in stairways, where the width can restrict this. Frantzich (1996) generated a graph which plotted the movement speed against the inter-person distance of people moving down stairways, see Figure 6. A comparison of the tests conducted by Frantzich down spiral stairs is represented as the red line in the graph, where the average inter-person distance was measured to be 0,7 m and velocities of between 0,50 and 0,55 m/s depending on the width of the stairs. In order to generate this graph, Frantzich made a small change to Equation 3 as follows:

$$d = \sqrt{\frac{1}{D}} \qquad \text{[Equation 13]}$$

Where D is the distance between occupants, see Figure 5.

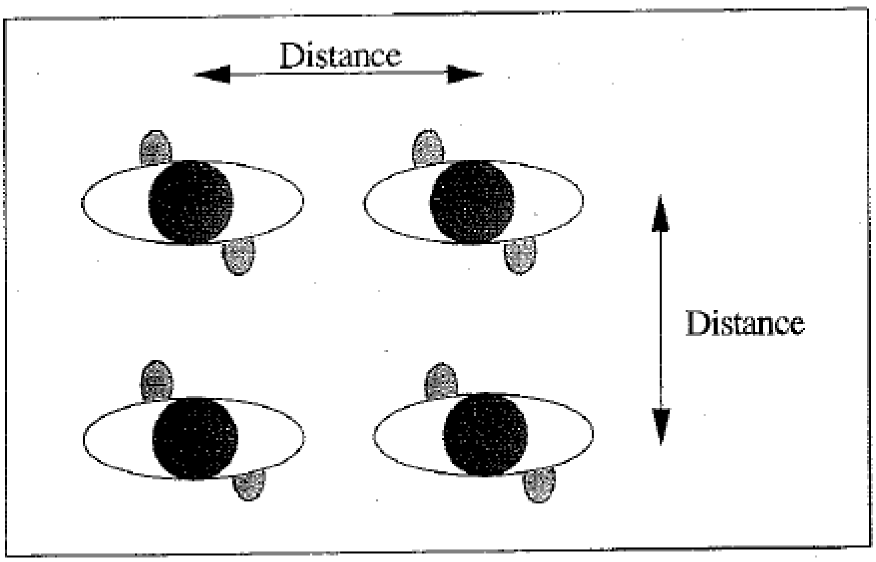


Figure 5. Inter-person distance, D.

According to Hoskins (2011), the number of empty treads and the measured density should be used under different circumstances and as independent variables. The number of empty treads should be used in more advanced computer models that take many other variables into consideration, but is not well suited to use in an algebraic equation. For the purpose of simple algebraic equations, the regularly used density measurement is more suited (Hoskins, 2011).

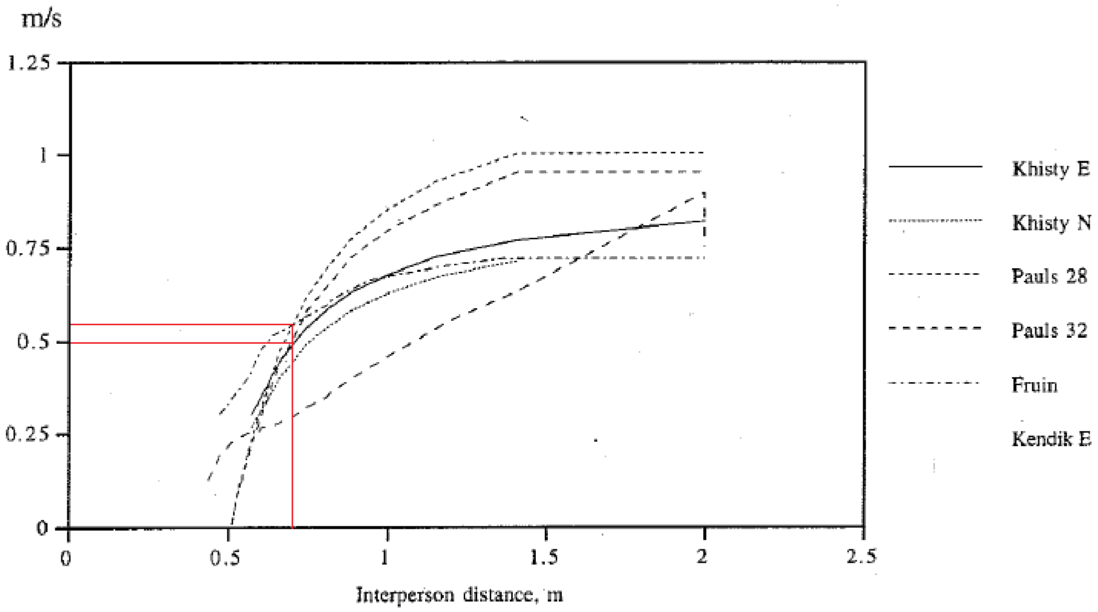


Figure 6. Graph displaying movement speed and interperson distance. Frantzich experiments are marked with the red lines. Original image taken from (Frantzich, 1996)

4 Building codes and regulations

In London, post-war building studies regarding the fire grading of buildings determined that spiral stairs should not have a diameter of less than 152 cm (Fire Grading of Buildings, 1952). Spiral stairs were restricted to be used by no more than 50 able-bodied persons and have an effective width to support at least one person. The following chapter reviews some changes that have been made in the last 60 years in the United Kingdom as well as in several other countries.

4.1 Sweden

The Swedish national building codes, BBR, contains regulations and general advice based on the construction act and constitution PBL and PBF. The code gives advice on building design, fire protection, egress and accessibility, and is applied to both new constructions and on reconstruction or renovation. The most recent version of the code is BBR 23 which was issued in 2016. (Boverket, 2016)

In clause 5:21, the BBR differentiates between different types of buildings depending on how it is being utilized and who is expected to reside in the building. The different building classes are listed below:

Vk1 – office buildings, where the residing people are expected to know their way around, and are able to get themselves to safety in case of emergency.

Vk2 – assembly halls and other premises where the residing people are not expected to know their way around, and do not require assistance to get themselves to safety. The term assembly hall is designated to a room or a group of rooms that are all within the same fire cell and is intended for a large number of people. This type of building is divided into three subgroups depending on the number of people on the premise and if alcohol is available:

- 2A – a maximum capacity of 150 people.
- 2B – a maximum capacity of more than 150 people.
- 2C – a maximum capacity of more than 150 people where alcohol is also available.

Vk3 – Residential buildings.

Vk4 – Hotels, hostels, bed and breakfast and other temporary accommodations.

Vk5 – includes premises where the residing people are in need of assistance to get to safety. This type of building is divided into four subgroups depending on what type of operation is conducted in it:

- 5A – premises that run activities mainly during the day, e.g. preschools, but includes premises that run activities during nighttime.
- 5B – sheltered housing for people who are physically or psychologically sick, suffer from dementia or who for other reasons are not capable to get themselves to safety.
- 5C – Hospitals and healthcare centers.
- 5D – premises for people who are locked up, such as prisons.

Vk6 – premises where there is a high risk of fire, such as mills and some industrial buildings. (Boverket, 2016, ss. 36-38)

BBR states in clause 5:334 that evacuation routes are required to have an unobstructed width of 0,9 m for premises with less than 150 residents, and an unobstructed width of 1,2 m for premises with more than 150 residents. Handrails are allowed to protrude no more than 0,1 m from each side of the evacuation route (Boverket, 2016, s. 53). The unobstructed height in evacuation routes is required to be 2 m (Boverket, 2016, s. 126).

With regards to egress using spiral stairways, BBR states that spiral stairways are not recommended to be used as an evacuation route for buildings of class Vk2B, Vk2C, Vk5B or Vk5C. In short, spiral stairways are not to be used for egress for premises where the residents have difficulty using stairs, or for premises where more than 150 residents are likely to be present. (Boverket, 2016)

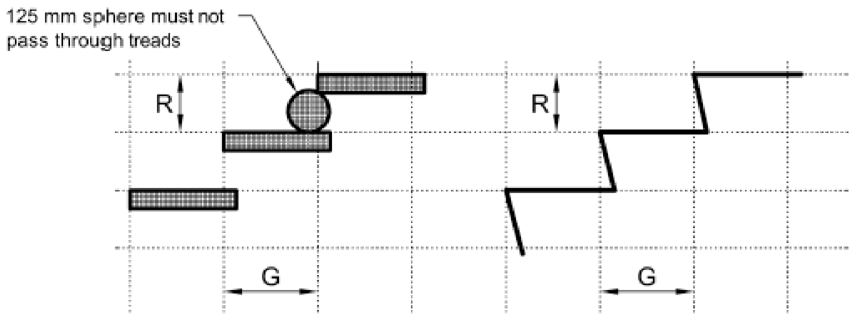
4.2 Australia

The National Construction Code, NCC, of Australia is similar to the BBR of Sweden. The NCC is maintained by the Australian Building Codes Board, ABCB, and is a compiled set of technical provisions for designing and constructing buildings. (NCC, 2016)

In Australia, a spiral stairway that is to be used as an evacuation route is required to have an unobstructed width of at least 1 m (NCC, 2016). The riser is required to be between 115 and 190 mm, and the tread (going) is required to be between 250 and 355 mm, see Figure 7. The NCC makes use of the French method of 2R + T, but denotes the tread as the Going (G). The red square marks information regarding spiral stairs.

Table D2.13 RISER AND GOING DIMENSIONS (mm)

	Riser (R)		Going (G) (2)		Quantity (2R+G)	
	Max	Min	Max	Min	Max	Min
Public stairways	190	115	355	250	700	550
Private stairways(1)	190	115	355	240	700	550



Notes:

1. Private stairways are—
   (a) stairways in a *sole-occupancy unit* in a Class 2 building or Class 4 part of a building; and
   (b) in any building, stairways which are not part of a *required exit* and to which the public do not normally have access.
2. The going in tapered treads (except winders in lieu of a quarter or half landing) in a curved or spiral stairway is measured—
   (a) 270 mm in from the outer side of the unobstructed width of the stairway if the stairway is less than 1 m wide (applicable to a non-*required* stairway only); and
   (b) 270 mm from each side of the unobstructed width of the stairway if the stairway is 1 m wide or more.

Figure 7. Restrictions regarding spiral stairs in the NCC. (NCC, 2016)

Noteworthy is that the NCC differentiate between the going in curved or spiral stairways that are less than 1000 mm wide and more than 1000 mm wide, although if the stair is to be used for egress it is required to be at least 1000 mm wide. (NCC, 2016)

Another noteworthy part of the NCC is that a stairway must have not more than 18 and not less than 2 risers in each flight, and as a required stairway, is not allowed to have winders (treads that are narrower on one side than the other) in lieu of a landing. (NCC, 2016)

4.3 New Zealand

The New Zealand Building Code, NZBC, is performance based. This means that it sets out criteria on how completed building work must perform, not how the work itself must be done (Ministry of Business, Innovation and Employment, 2014). This flexibility makes it possible for compliance with the Building Code to be demonstrated in different ways, the most common being the Acceptable Solutions and the Verification Methods. These provide details for a construction that will comply with the Building Code if they are followed.

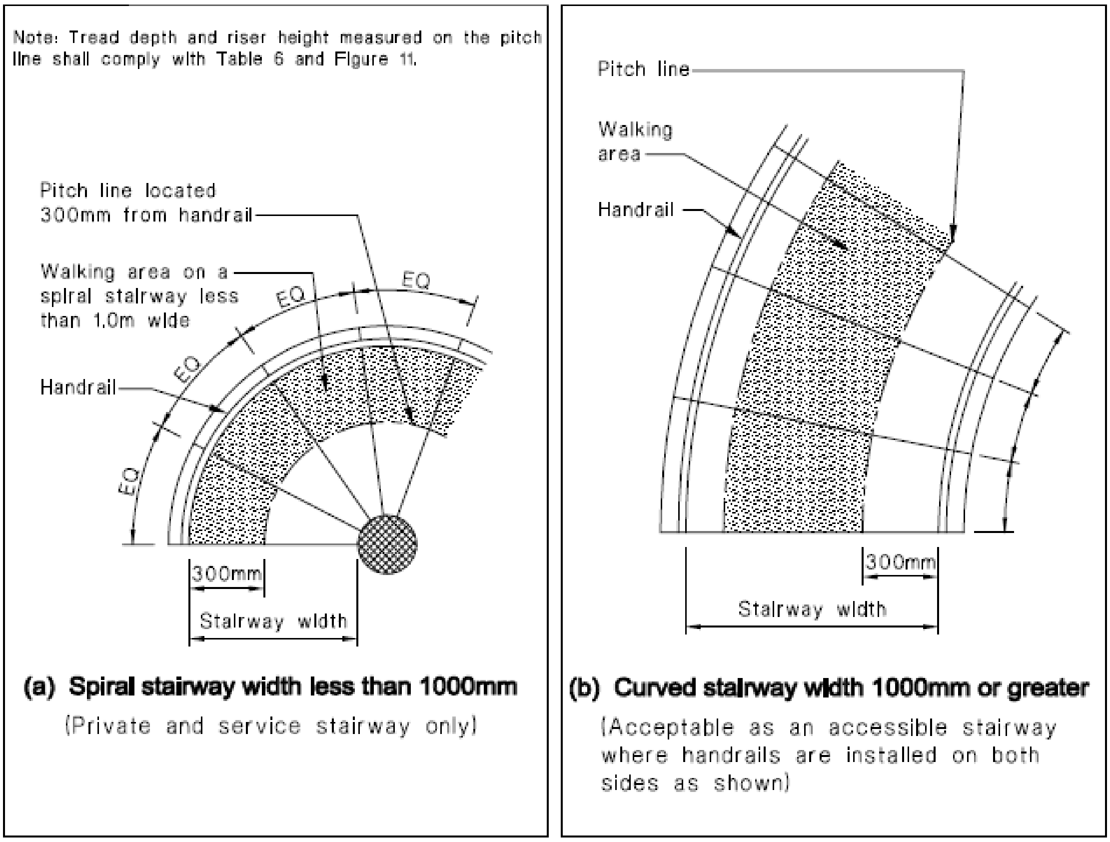


Figure 8. Design limits for narrow and wide spiral stairs in New Zealand. (Department of Building and Housing, 2011)

Acceptable Solution document D1/AS1 (2011) states that the required width of spiral stairs is described as the walking area and is illustrated in Figure 9 below. New Zealand also differentiates between where the pitch line, or going, is located for stairs that are less than or greater than 1000 mm.

Clause 4.4.1 in D1/AS1 states that the acceptable width between handrails of a stairway should be no less than 900 mm (Department of Building and Housing, 2011). The design limits for the riser, tread and pitch line slope are presented below in Table 4, taken from clause 4.1 in D1/AS1. The values differ from the design rule of twice the rise plus the going (2R+G) that is used by Australia (and others) which is not considered to always lead to a safe geometry of the stairway (Department of Building and Housing, 2011). The tread is measuring along the pitch line, which can be interpreted as the line of going. Acceptable Solution D1/AS1 'prefer' a pitch slope of between 23° and 37°, and that a slope between 37° and 47° is not for general use. Anything above is considered unsafe. A slope between 18° and 23° is uncomfortable and anything below 18° should be used for ramps, not stairs.

Table 4. Design limits for spiral stairways in New Zealand.

Stair	Maximum pitch slope	Maximum riser height [mm]	Minimum tread [mm]
Service, minor private	47°	220	220
Secondary private	41°	200	250
Common and main private	37°	190	180
Accessible	32°	180	310

4.4 UK

The Building Regulations in the United Kingdom state that spiral stairways may form part of an escape route if they are designed in accordance with the standard BS 5395-2 (Department for Communities and Local Government, 2013). Depending on if the stairway is intended for private or public use, and the number of people who are expected to use it, the following dimensions apply, see Table 5 (British Standards Institution, 1984).

Table 5. Allowed dimensions for spiral stairways according to the standard BS 5395-2.

Stair category	Riser height [mm]	Tread width [mm]			Minimum clear width [mm]	Quantity, 2R+G [mm]
		Inner minimum	Centre minimum	Outer maximum		
A (small private)	170-220	120	145	350	600	480-800
B (private)	170-220	120	190	350	800	480-800
C (small semi-public)	170-220	150	230	350	800	480-800
D (semi-public)	150-190	150	250	450	900	480-800
E (public)	150-190	150	250	450	1000	480-800

The number of treads for each 360° rotation of the stairs should vary between 15 and 16. The going in spiral stairways is measured 270 mm from the unobstructed width from each side of the stair, regardless of width (British Standards Institution, 1984).

4.5 USA

Clause 7.2.8.4 in the NFPA 101 Life Safety Code, it is clearly stated that spiral stairways are not to be used for premises where the occupant load exceeds ten. It has specific criteria for premises where the occupant load does not exceed five persons, and other specific criteria for premises where the occupant load does not exceed three persons in Clause 7.2.2.2.3. Generally, the riser heights shall not exceed 180 mm and the tread shall not be less than 280 mm for a specific width of the stair. Handrails are required to be installed on both sides of the stairway and the turn of the stairway shall be so that the outer handrail is to the right of users who are descending. (National Fire Protection Association, 2012)

4.6 Canada

The National Building Code, NBC, of Canada provides technical provisions for the design and construction of new buildings, as well as reconstruction, renovation and demolition of existing building. (Canadian Commission on Building and Fire Codes, 2010)

Clause 3.3.1.16 in the NBC simply states that "*A curved or spiral stair is permitted in a stairway not considered as an exit*" (Canadian Commission on Building and Fire Codes, 2010). The clause later provides acceptable tread dimensions, but as it is not considered a viable means of egress, this will not be considered further.

4.7 Summary of building codes

When comparing the different countries' codes, they vary from country to country. The differences in the maximum occupant load that is allowed for the use of spiral stairways as an egress route is summarized in Table 6.

Table 6. Occupant load restrictions for using spiral stairways in different countries.

	Sweden	Australia	New Zealand	United Kingdom	USA	Canada
Maximum occupant load	150	No limit	No limit	No limit	10	-

The recommended dimensions when constructing spiral stairs also vary between countries, although the differences may be marginal in some cases. Table 7 below summarizes the different dimensions that are allowed in the different countries. Canada is omitted since spiral stairs are not allowed in evacuation routes. The values for Sweden are based on BBR, chapter 8:232. A dash means that the value was not presented or unavailable in the Building Code for that country.

Table 7. Summary of allowed dimensions of spiral stairways in different countries.

	Riser [mm]	Tread [mm]	(2R+G) [mm]	Pitch slope	Width [mm]	Pitch line position from centre/edge [mm]
Australia	115-190	240-355	550-700	-	1000 (min)	270/270
NZ	220 (max)	180 (min)	-	23°-47°	900 (min)	300/300 (wide/narrow)
UK	150-220	120-150, 145-250, 350-450	480-800	-	600-1000 (min)	270/270
USA	180 (max)	280 (min)	-	-	-	-
Sweden	160 (min)	250 (min)	590-630		900-1200 (min)	-/250

5 Experiments

5.1 Experimental setup

5.1.1 Geometric description of the stairs

Three different sets of spiral stairs have been utilized for the experiment. All the stairways are located on the campus of the University of Canterbury. This made it possible to conduct the experiment using the same participants in all the stairways. The stairways have differing dimensions that are described in Table 8 below. A fourth stairway has been used, but it is not of a traditional spiral build so the data will not be used to draw any conclusions in deriving an equation of population flow in this report. The stairs in Table 8 are shown in the order that they were used in the experiment.

Table 8. Dimensions of stairs used for the study. Going is defined by the NZBC in section 4.3 as the pitch line. Pitch slope is calculated in the going of each stair.

Stairway #	Newel diameter [mm]	Total Width [mm]	Inner tread [mm]	Outer tread [mm]	Tread in going [mm]	Riser [mm]	Pitch slope
1	1380	1420	200	560	276	180	33°
2	310	600	110	310	210	190	42°
3	320	1000	-	400	280	175	32°
4	1120	1120	280	280	280	200	36°

Stairway 1

Stairway 1 is an internal stair and is wide and open, with large, round handrails on both sides, see Figure 9. The treads are made of concrete with a polished wood surface and have a metal lining on the edges, most likely to increase visibility of the edges. It spans one floor and is in an open atrium-like space which gives it an airy feeling. It has a landing four treads from the top that has an area corresponding to three treads. After the landing, there are an additional 13 treads.

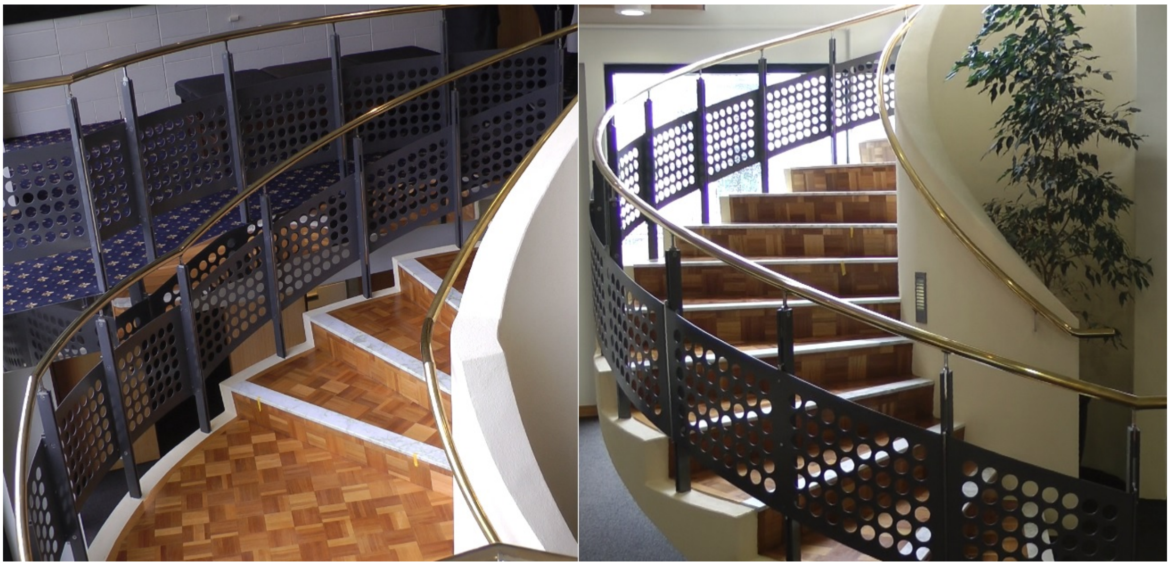


Figure 9. Stairway 1.

Stairway 2

This stairway is in a small library to give access to books on a mezzanine-like second story. With its 60-cm width, it is a narrow stairway which is free standing. The treads are made by wooden plates with a rubber surface. The stair has a handrail on the outer side, see Figure 10. Important to note is that the treads do not connect with the newel, but are cut off 100 mm from the newel. This can be interpreted as though the newel is wider since the treads begin further from the center of the spiral. The stairway has a total of 12 treads.

Figure 10. Stairway 2.

Stairway 3

Stairway 3 is located outside and gives access to a walkway between two buildings. It spans one story and is free standing but is of a concrete build which gives it a good stability. The treads are made of rectangular concrete blocks tucked in beneath one another. The outer side of the stairs is solid and made of concrete, see Figure 11. The stair has a handrail along the outer side, and does not have a landing. The stairway has 20 treads in total.

Figure 11. Stairway 3.

Stairway 4

This stairway serves as an external evacuation route for one of the buildings on campus. It spans several stories and is not closed off to the outside, giving an open and airy feel to it. The solid concrete newel and metal cylinder cage serve as support and gives way for a very stable descent.

However, there are a few aspects of the stairway that sets it apart from a traditionally built spiral stairway. One of these aspects is that the treads are not of the typical triangular shape, but are instead almost completely rectangular. This is made possible due to that after every two treads there is a landing, see Figure 12. The landings make up most of the rotation around the newel, which allow the few treads there are to be shaped in this way, and are therefore comparable to treads that are used in regular straight stairways. Another aspect that sets the stairway apart is that it does not have a handrail on the outer side, but instead has one on the inner side against the newel.

This stairway is not of interest for the objective to derive an equation for population flow in spiral stairs. It could, however, be interesting to consider how it performs in comparison with the others stairways, and especially how it is perceived by the participants. It would be interesting to see how the landings impact the gait of the persons using the stairs.

Figure 12. Stairway 4.

5.2 Participants

A total of 25 participants took part in the experiments, with a good distribution of different ages, although the majority were 30 years or younger. There were 12 men and 13 women. Three of the participants were left-handed and the rest were right-handed. The distribution of age of the participants is illustrated in Figure 13. Due to other commitments, a few of the participants were only available for a few of the tests. Not all participants chose to fill out the questionnaire, as this was voluntary.

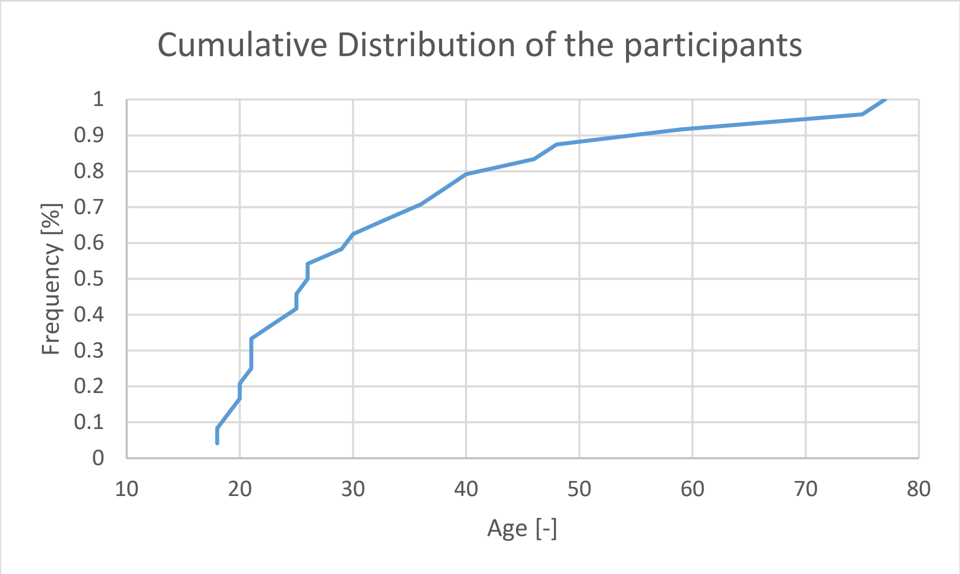


Figure 13. Age distribution of participants.

The participants were recruited using various forms of social media, email and by individual recruitment in the University of Canterbury Library. Each participant was asked to invite friends and family. The information given to the participants are presented in Appendix B.

5.3 Documentation

Two video cameras were used to document the experiments. One was placed at the bottom of each stair to document the flow at the end of the stairway, and the other camera was placed to give an overview of each stairway to document behavioral patterns and movement speed of the participants. Due to restricted access to suitable location, only one camera was used to document Stairway 4. This camera was located halfway down the stairs and used to document both population flow and behavioral patterns.

After the experiments, the participants of the study were required to fill out a questionnaire, see Appendix A, to express their opinion and give an insight on how the stairs were perceived.

5.4 Experiments

A variety of different tests were conducted in each stairway. The participants were instructed to use the stairs as they would on a normal day under normal circumstances, to avoid imposing any different behavioral pattern on them. Two exceptions were made in Stairway 1 as described in Table 9 below. The reason that the number of participants vary in some stairways is that some participants showed up late or could only participate for a limited time.

Table 9. Description of experiments.

Stairway 1	**Description of test**	**No. of participants**
Test 1-1	Normal circumstances	24
Test 1-2	Normal circumstances	24
Test 1-3	Normal circumstances	24
Test 1-4	Normal circumstances	25
Test 1-5	Participants instructed to use outer part of stairway only	25
Test 1-6	Participants instructed to use inner part of stairway only	25
Stairway 2		
Test 2-1	Normal circumstances	24
Test 2-2	Normal circumstances	24
Stairway 3		
Test 3-1	Normal circumstances	19
Test 3-2	Normal circumstances	22
Stairway 4		
Test 4-1	Normal circumstances	21
Test 4-2	Normal circumstances	23

6 Results of experiments

The following chapter presents the documented population flow, movement speed and utilized width that were observed during the experiment. Values for Stairway 1, 2 and 3 will be documented below, whereas the values for Stairway 4 will not.

6.1 Population flow and movement speed

The population flow is measured at the bottom of each stairway, and is measured as the time from when the first participant exits the stairway to when the last participant exits the stairway. The movement speed is measured in the slope of the stairway in the observed line of going. Using the tread depth in the observed line of going, the riser height and the number of treads in each stairway made it possible to calculate the total distance covered by the participants. Dividing this distance with the average time it took for each participant to cover the distance resulted in an average movement speed in each stairway. In Stairway 1, the participants used one of three tread positions; the outer, middle or inner, see Figure 14. The treads are observed to be an equal distance apart from each other, and are 53 cm, 76 cm and 99 cm from the inner side of the stairs. Important to note is that although there are three different treads, the stair is only wide enough for two occupants to walk side by side. If the middle tread is used by a participant, there will be no space for other participants on their sides. Stairways 2 and 3 have only one observed line of going. The documented results are presented in Table 10.

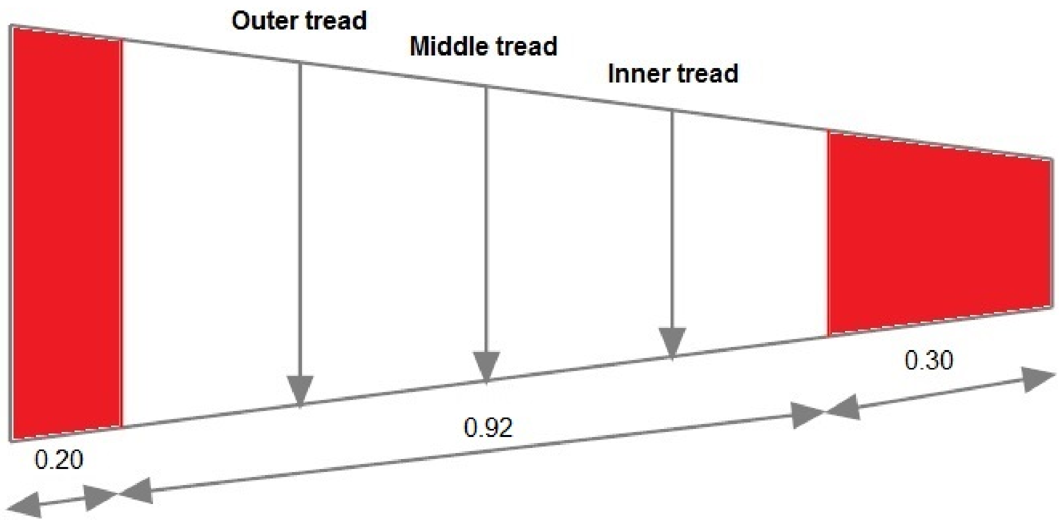


Figure 14. The three used tread depths in Stairway 1. The red parts represent the observed area of the treads on which the participants did not put their feet.

Table 10. Documented population flow and movement speed for each test in the different stairways. Stairway 1 has three observed lines of going. Stairways 2 and 3 each have one observed line of going.

Stairway #	Test #	Population flow [p/s]	Movement speed [m/s]		
			Outer	Middle	Inner
1	1-1	1.60	0.95	0.91	0.70
1	1-2	1.85	0.97	0.93	0.72
1	1-3	1.33	0.93	0.89	0.69
1	1-4	1.39	0.93	0.89	0.69
1	1-5 (Outer lane)	0.83	0.88	-	-
1	1-6 (Inner lane)	0.76	-	-	0.77
2	2-1	0.52		0.49	
2	2-2	0.52		0.53	
3	3-1	0.66		0.68	
3	3-2	0.63		0.68	
4	4-1	0.75		-	
4	4-2	0.70		-	

6.2 Utilized width

The document width of each stairway that is efficiently utilized by the participants is presented in Table 11. The utilized width is measured as the total width on which the participants put their feet while descending each stair. The theoretical effective width of each stairway is also presented, and is based on Pauls method regarding regular straight stairs, which is 15 cm from each side.

Table 11. The total width, effective width (as described by Pauls), observed used width and the smallest used tread depth.

Stairway #	Total width [m]	Effective width [m]	Documented utilized width [m]	Smallest utilized tread [mm]
1	1.42	1.12	0.92	276
2	0.60	0.30	0.33	170
3	1.00	0.70	0.41	176

The documented distance that the participants kept from the inner and outer side of each stairway is presented in Table 12. The distance is measured from where the participants put their feet while descending the stairs.

Table 12. Documented distance that the participants kept from the outer and inner side of each stairway.

Stairway #	Distance from outer side [m]	Distance from inner side [m]
1	0.20	0.30
2	0.09	0.18
3	0.15	0.44

6.3 Density and inter person distance

Two different methods are used to measure the population density on each stairway. The first method that is used is calculated as the number of occupants per unit area on the stairway, and the second method measures the empty number of treads between the occupants, or the inter-person distance. Both methods are described in more detail in section 2.5. The inter-person distance is approximated as the distance of the number of empty treads between occupants plus one additional tread, under the assumption that the participants are always at the center of each tread.

When calculating the population density in Stairway 1, it is of interest how many of the occupants utilized the inner and outer lane, and how many that moved down in the middle of the stairway. Table 13 presents the calculated density, number of empty treads between occupants, and percentage of participants who used which lane during the tests down Stairway 1. It is important to recall is that in test 1-2, all the participants used either the outer or inner tread position in the stairs; no participant used the middle tread position. This may explain why test 2 has the largest documented population flow.

Table 13. Calculated density, empty number of treads between participants and percentages of which part of Stairway 1 was used. All values are average.

Stairway 1	Density [p/m^2]	No. of empty treads [-]	Inter-person distance [m]			Used part of stair [%]		
			Outer lane	Inner lane	Between lanes	Outer	Middle	Inner
Test 1-1	1.6	1.3	1.04	0.77	0.70	50	17	33
Test 1-2	1.6	1.1	0.95	0.70	0.70	54	0	46
Test 1-3	1.3	1.5	1.13	0.84	0.70	50	17	33
Test 1-4	1.4	1.3	1.04	0.77	0.70	56	8	36
Test 1-5 (Outer)	1.5	1.0	0.9	-	-	100	0	0
Test 1-6 (Inner)	2.2	1.8	-	0.94	-	0	0	100

For the remaining stairways, the calculated density, the number of empty treads between participants and the inter-person distance is presented below in Table 14.

Table 14. Calculated population density and number of empty treads between participants in Stairway 2 and Stairway 3. All values are average.

Stairway 2	**Density [p/m²]**	**No. of empty treads [-]**	**Interperson distance [m]**
Test 2-1	2.9	1.9	0.92
Test 2-2	2.9	1.9	0.92
Stairway 3			
Test 3-1	1.9	1.7	1.07
Test 3-2	1.9	1.8	1.11

6.4 Derived equations

The following section presents the derived equations for movement speed and population flow in spiral stairways.

6.4.1 Movement speed

To derive an equation for the movement speed, the measured speed in each test is plotted against different variables. By using linear regression, a best-fit line for each variable was produced. The variables that are found to have the largest impact on the movement speed are the square root of the ratio between the tread and riser, and the population density of the occupants. Figures 15 and 16 illustrates the relationship between the variables and the speed. The ratio between the tread and the riser was also found to have a large impact on the movement speed, with a correlation similar to that of the square root of the ratio. However, by using the square root of the ratio, the spread of the values decreased, making for a less sensitive variable.

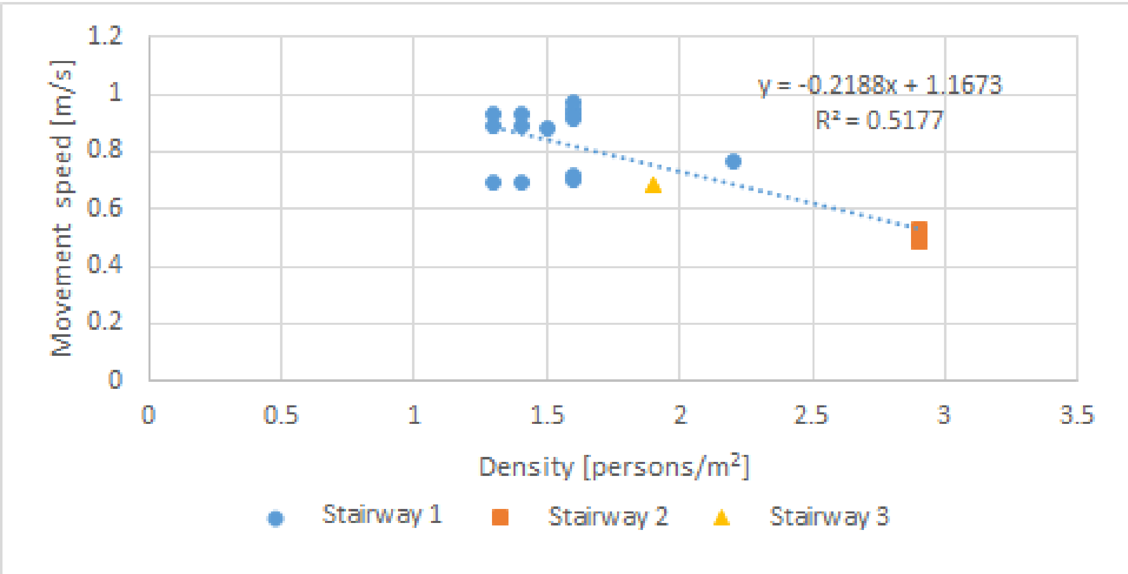


Figure 15. Relationship between density and movement speed.

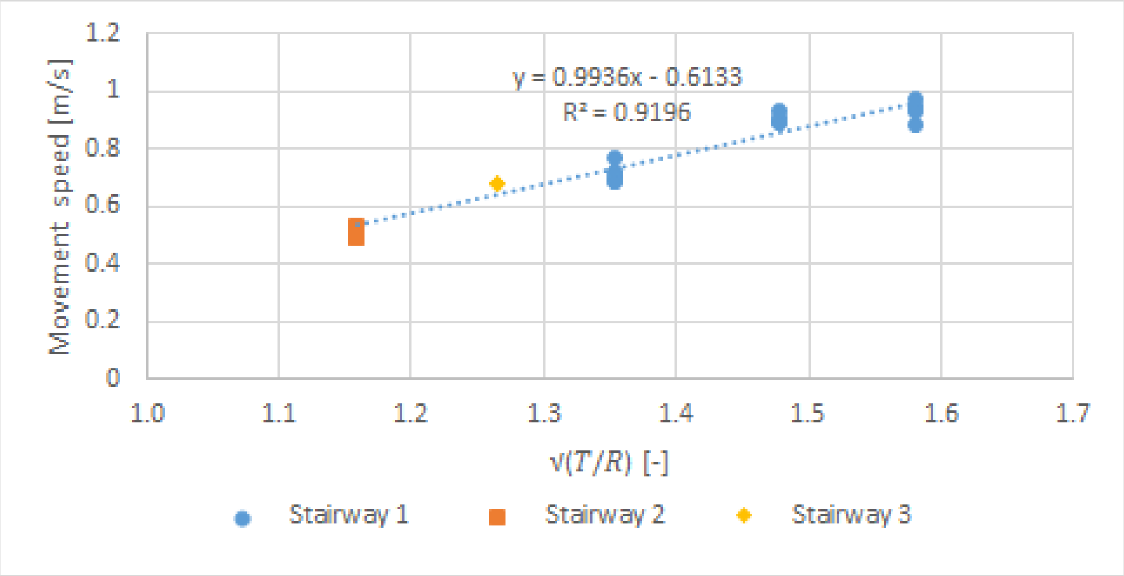


Figure 16. Relationship between the tread and riser, and the movement speed.

Based on the relationship between the movement speed and the variables above, a suggested equation for determining movement speed of individuals descending spiral stairs is presented below.

$$S = k - akD \qquad \text{[Equation 14]}$$

S = movement speed [m/s]

D = Population density [persons/m^2]

$k = 0.8\sqrt{\frac{T}{R}}$ [-]

$a = 0.177$ [-]

T = Tread depth in line of going [m]

R = Riser height [m]

When simplified by taking $\sqrt{\frac{T}{R}}$ out of the bracket and multiplying in the constants, the equation can alternatively be written as:

$$S = 0.14\sqrt{\frac{T}{R}}(5.7 - D) \qquad \text{[Equation 15]}$$

Equation 14 is identical to Equation 8 presented by (Gwynne & Rosenbaum, 2008), apart from that the k-value is calculated differently and that the constant *a* is different. The k-value is however calculated in a similar way to Buchanan (2001). The used density, D, is calculated on the entire area of the treads. The presented equations are therefore independent of both the width of the stairway and the newel diameter. The equation allows for a density of up to 5.7 persons per square meter, which is higher than the maximum allowed density for using Equation 8 at 3.8 persons per square meter.

For design purposes, it is of interest to be able to calculate the tread in the line of going. The tread in the going is found to be dependent on the outer tread depth of the stairs, see Figure 17. The proposed method on how to calculate the tread depth in the going, T, is approximately equal to three quarters of the outer tread depth, T_O:

$$T = 0.75T_O \qquad \text{[Equation 16]}$$

T = Tread depth in going [m]
T_O = Outer tread depth [m]

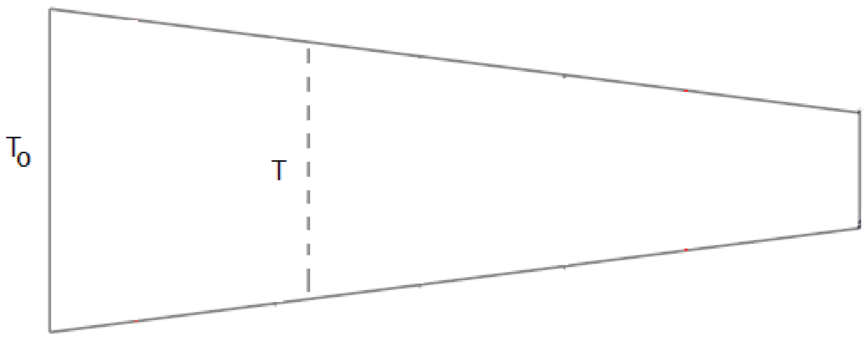


Figure 17.The outer tread depth ,T_O, is required to calculate the tread in the going in spiral stairways.

A comparison of the calculated tread in the going and the actual tread in the going is presented in Table 15 below. The different calculated movement speeds are also presented for comparison.

Table 15. Comparison between the observed tread and the calculated tread using Equation 13. The movement speeds have been averaged over the documented densities.

Stairway #	Actual tread [mm]	Calculated tread [mm]	Movement speed (actual tread)	Movement speed (calculated tread)
1 (Middle)	393	420	0.90	0.90
1 (Outer)	450	420	0.93	0.90
1 (Inner)	330	290	0.71	0.63
2	255	230	0.45	0.43
3	280	300	0.68	0.70

Figure 18 illustrates the relationship between the measured movement speed and the calculated movement speed using Equation 14 and 16, and Figure 19 below illustrates how Equation 14 correlates with the documented values for movement speed using the actual tread depth in the line of going. The blue circles represent values from Stairway 1, the orange squares represent Stairway 2, and the yellow diamonds represent Stairway 3. The red triangles represent values from Frantzich (1996) study and have not been used to derive Equation 13.

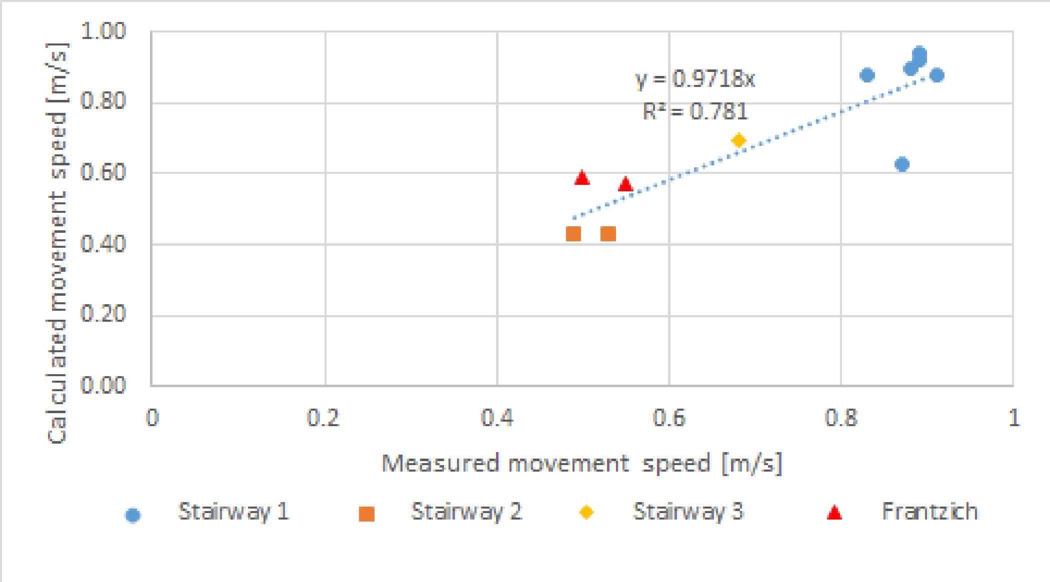


Figure 18. Correlation between the measured movement speed and the calculated movement speed using the Equation 15 to calculate the tread in the going.

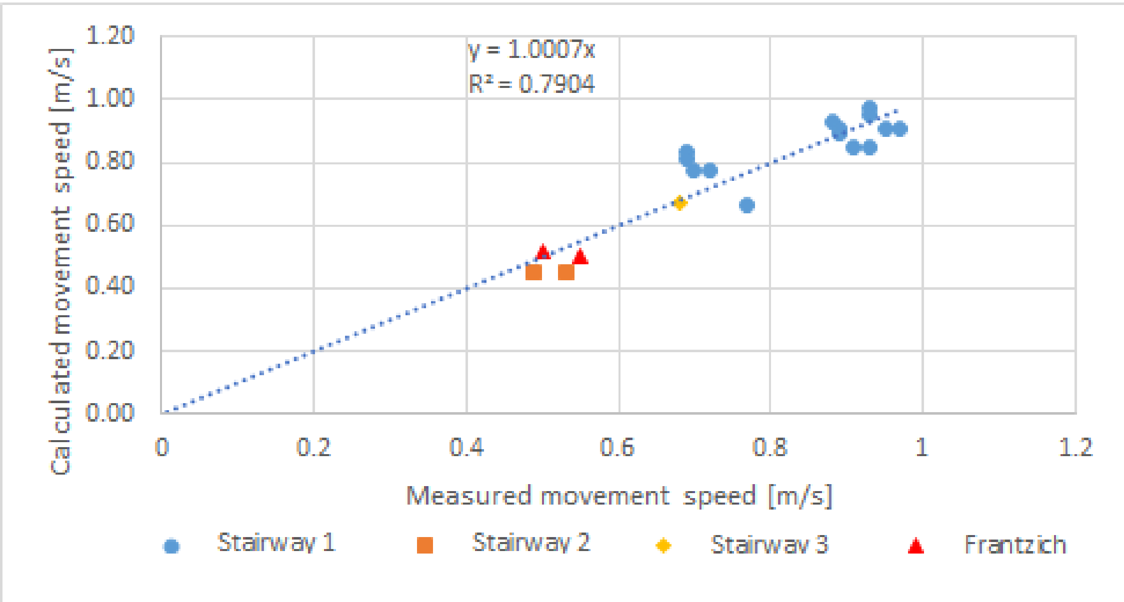


Figure 19. Correlation between the calculated and measured movement speed.

The calculated values using Equation 14, both with a tread depth calculated using Equation 16, and when using the tread depth in the observed line of going produce the above correlations when plotted against the measured values. The produced best-fit line for both graphs also have high R^2-values at 0.78 and 0.79 which indicates that the calculated movement speed is approximates the measured movement speed accurately.

Equation 14 is linearly dependent on the population density. Figure 20 serves as a comparison of the equations presented by Gwynne & Rosenbaum, where the red lines represent the calculated values in spiral stairs using Equation 14 presented in this report, and the blue lines represent the values in straight stairs using the equation presented by Gwynne & Rosenbaum. Gwynne & Rosenbaum assume that at a density less than 0.5 persons/m^2, occupants in stairs move at a constant speed, and that a density greater than this will impact the movement speed. No such assumption is made for movement in spiral stairs. An interesting observation is that the calculated movement speed in spiral stairs is higher than in straight stairs with the same treads and risers. Important to note that Equation 13 and 15 are only validated for a population density between 1.3 and 2.9 persons/m^2, and that it is an assumption that the movement speed follows a linear relationship with an increased density. It is also important to note that Gwynne & Rosenbaum derived their equation based on conservative assumptions and will therefore produce lower values.

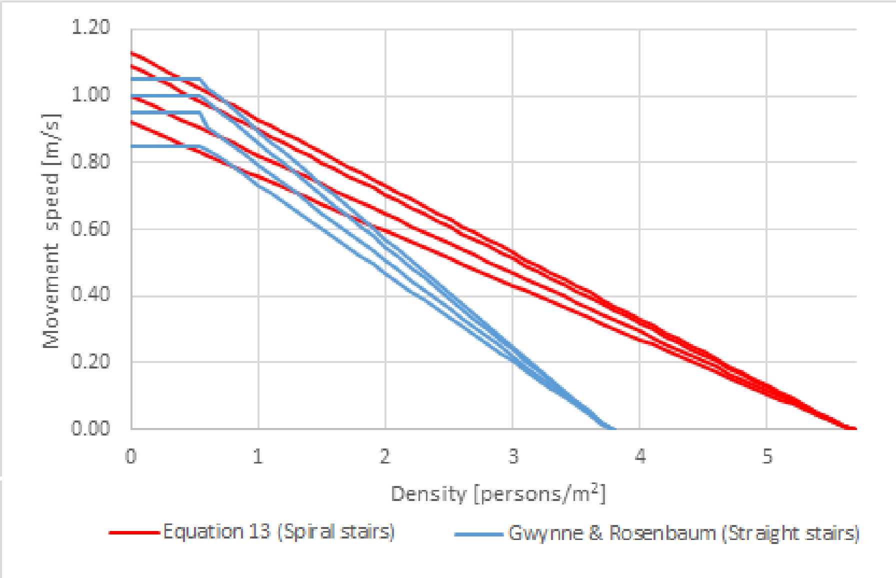


Figure 20. Comparison between Equation 13 and the equations proposed by Gwynne & Rosenbaum for straight stairs with the same tread/riser relationship.

6.4.2 Population flow

To derive an equation for population flow in the stairs, a check is made to see how well the fundamental traffic equation correlates with the measured flow-values. The population density, the movement speed and the width of each stair is plotted against the measured flow in Figure 21 to 23, where a linear best-fit line is produced for each variable. The middle tread in Stairway 1 is used when calculating the movement speed to give an average speed.

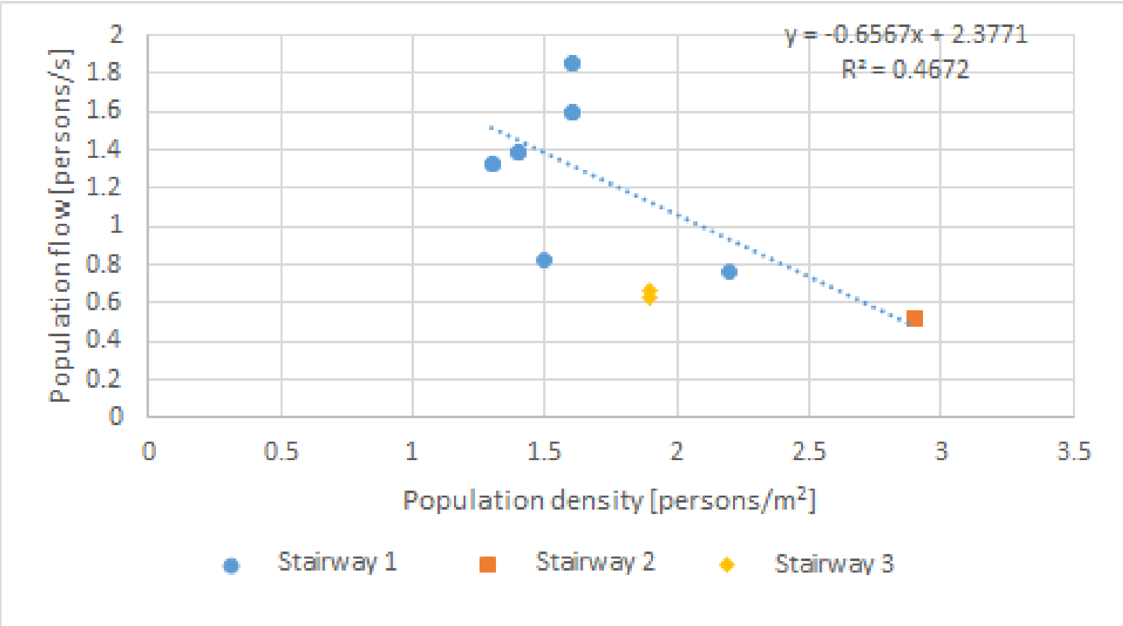


Figure 21.Relationship between the population flow and the population density.

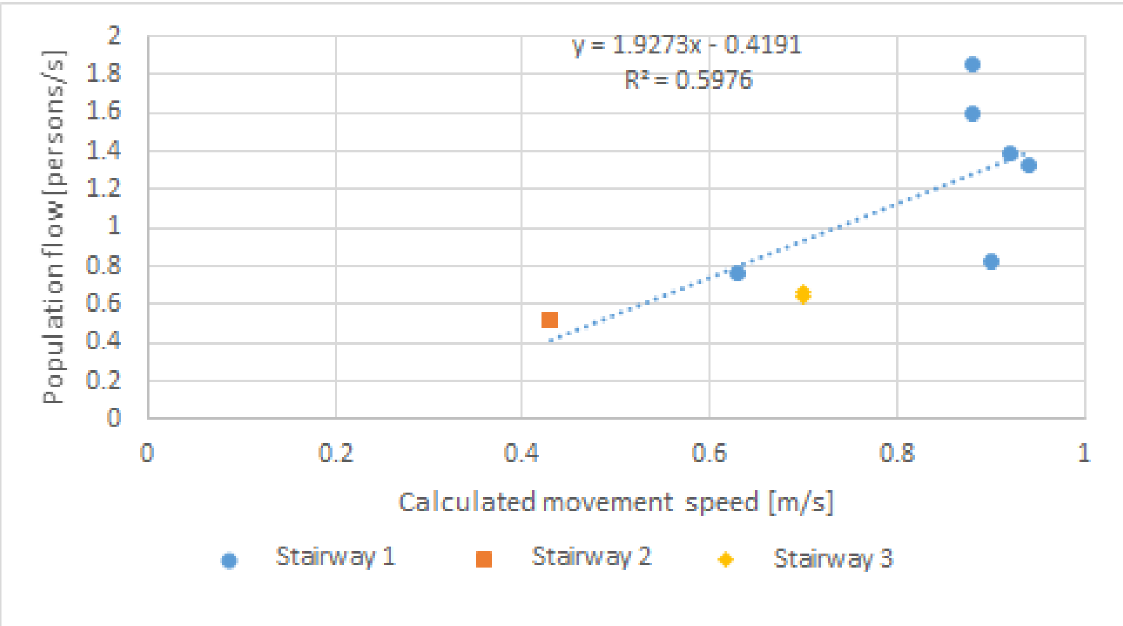


Figure 22.Relationship between the population flow and the calculated movement speed using Equation 13 and 15.

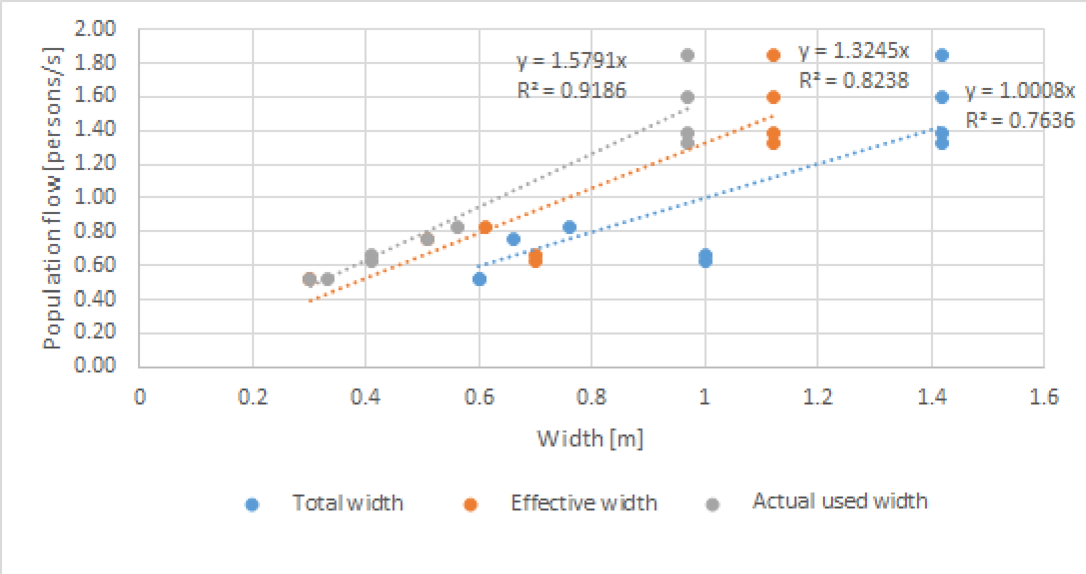


Figure 23. Relationship between the population flow and the width of the stairways.

The produced best-fit line for correlation between the population flow and the population density, and the population flow and the movement speed have R^2-values of 0.47 and 0.60 respectively, whereas the correlation between the flow and width is better, with an R^2-value of 0.82 for the effective width defined by Pauls (1984). The suggested equation for calculating population flow down spiral stairways is therefore the fundamental traffic equation:

$$F_c = SDW_e \qquad \text{[Equation 17]}$$

F_c = calculated population flow [persons/s]

S = movement speed [m/s]

D = population density [persons/m^2]

W_e = effective width as defined by Pauls (1984) for straight stairways [m]

Values for movement speed and population density are the same as from Equation 14. The average movement speed is used to calculate the flow in Stairway 1. The effective width is calculated using Pauls (1984) method. Equation 17 can be expressed in an alternative way:

$$F_c = (1 - aD)kDW_e \qquad \text{[Equation 18]}$$

$k = 0.8\sqrt{\frac{T}{R}}$ [-]

$a = 0.177$ [-]

T = Tread depth in line of going [m]

R = Riser height [m]

Equation 17 and 18 are identical to Equation 10 presented in (Gwynne & Rosenbaum, 2008). Figure 24 illustrates how well the measured flow correlates with the calculated flow using Equations 14 and 16. An interesting observation is that the calculated population flow is dependent on the tread, riser, population density and width of the stairway, just like regular straight stairways. Using the actual width used by the participants gives a calculated flow that is generally lower than when using the effective width. The effective width presented by Pauls (1984) should therefore be used when calculating the flow. The resulting best-fit line estimates the calculated population to be 98% of the measured population flow, and produces an R^2-value of 0.85.

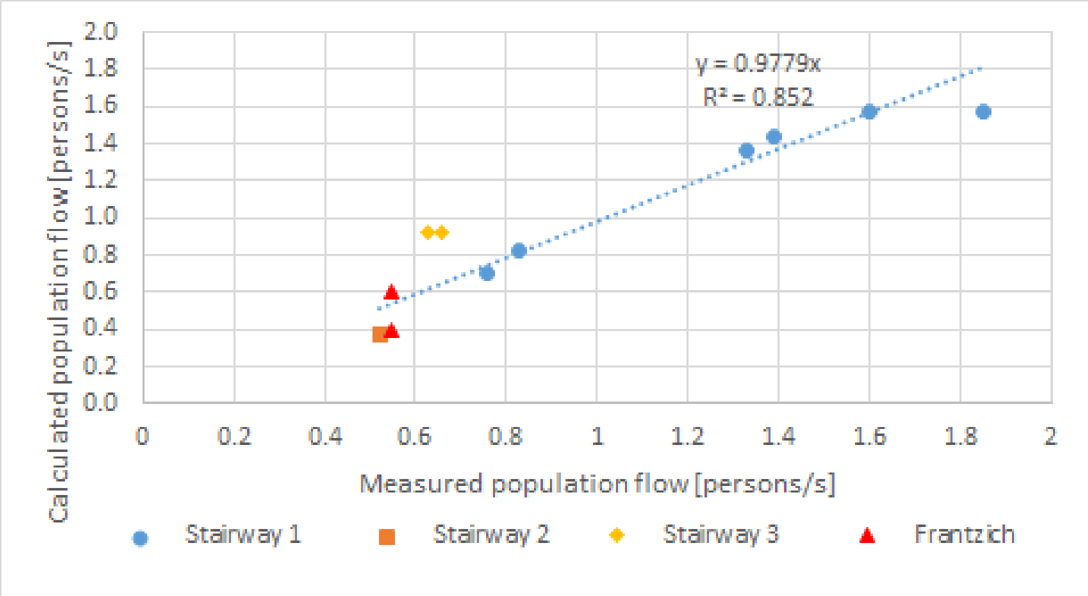


Figure 24. Correlation between the calculated and measured population flow.

It is again important to note that Equation 17 and 18 are only validated for a population density between 1.3 and 2.9 persons/m^2. Figure 25 presents a comparison of the specific flow based on Equation 16 and the equation presented by Gwynne & Rosenbaum for straight stairs. Since the population flow is dependent on the movement speed, it is again observed that the calculated flow in spiral stairs, calculated using Equation 17 is higher than the calculated population flow in straight stairs with the same tread and riser relation.

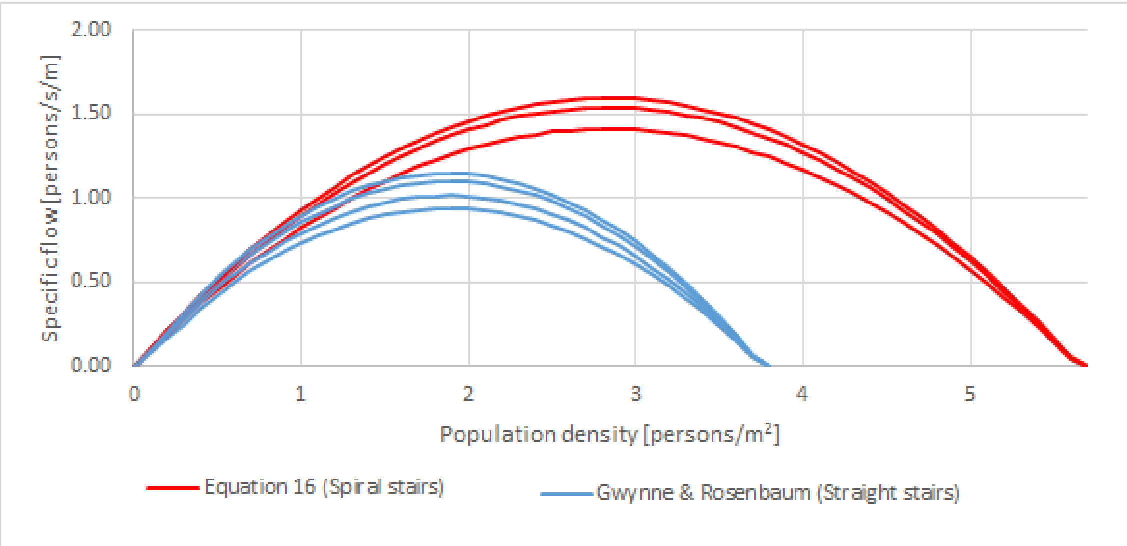


Figure 25. Comparison between the calculated specific flow using Equation 16 and the equations proposed by Gwynne & Rosenbaum for straight stairs with the same tread/riser relationship.

6.5 Questionnaires

This section presents the results from the questionnaires (see appendix A) that the participants were asked to fill out. Results from all four stairways are brought up and the comments written down by the participants are presented below.

Not all of the participants chose to fill out the questionnaire as this was voluntary, and some of the participants were only available for a few of the tests, see Table 9. Table 16 below presents the number of participants who filled out the questionnaire for each stairway.

Table 16. Number of filled out questionnaires.

	Stairway 1	**Stairway 2**	**Stairway 3**	**Stairway 4**
Number of filled out questionnaires	24	23	21	22

6.5.1 Question 1 – How did it feel moving down the stair?

When asked to rate how easy it felt to move down the stairs, the participants produced the following response, see Figure 26.

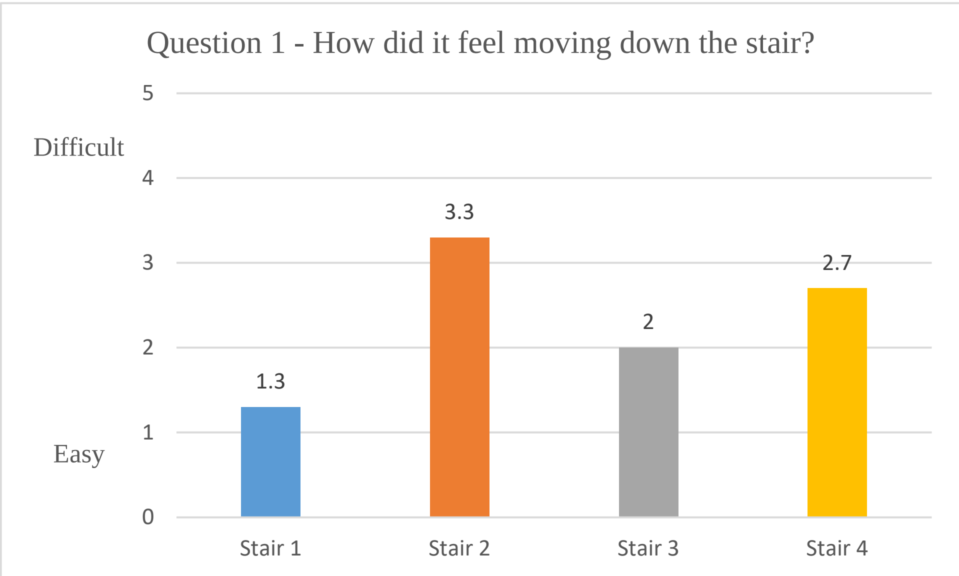


Figure 26. Graphic representation of Question 1.

The overall perception of Stairway 1 is that they are nice and wide, and that there was an easy flow due to the width, making it easy to walk side by side. Other comments include that the speed is restricted by other, slower participants and one comment was made that the landing was of a smaller annoyance.

The comments made about Stairway 2 describe the stairs as small, narrow and '*wobbly*'. Many of the participants express that they are more cautious when using the stairs and that takes more concentration. A few positive comments are made stating that the fact that the stairs require a single file makes for an easier descent.

Few comments are made regarding Stairway 3 apart from that it was scary using the stairs in the rain, and that some of the participants find themselves hugging the newel.

6.5.2 Question 2 & 3 – Did you pass anyone/Did anyone pass you?

According to the questionnaires, passing only occurred in Stairway 1 and Stairway 4. One participant claimed to have passed another individual in both stairs, and two participants claim to have been passed in both stairs. This indicates that the same participant passed more than one individual, or that some of the participants did not notice that they had been passed.

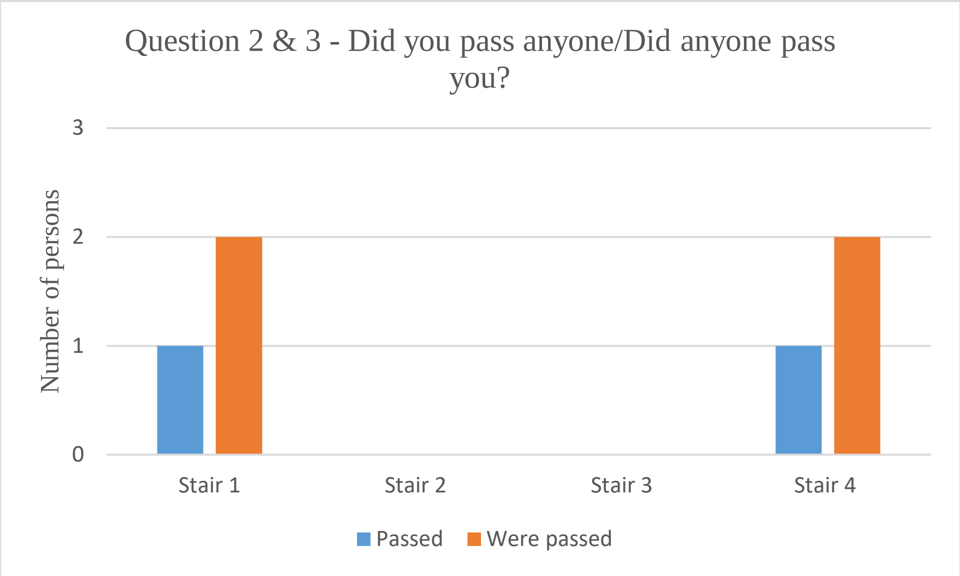


Figure 27. Number of participants who passed others or were passed themselves.

Question 2a & 3a – If yes, how did it feel?

When asked how it felt when passing or being passed the answer varies between Stairway 1 and Stairway 4, see Figure 28. The comment made about passing in Stairway 1 is *"Relatively easy due to width of stairs"*, compared to the comment *"I was confused about whether there was enough space to pass"* made about passing in Stairway 4.

Similarly, comments made about being passed down Stairway 1 say there is *"Lots of room"*, and comments about Stairway 4 include *"Didn't see why he needed to, it felt awkward"*, and *"Felt cramped, like I needed to speed up. I didn't like it"*.

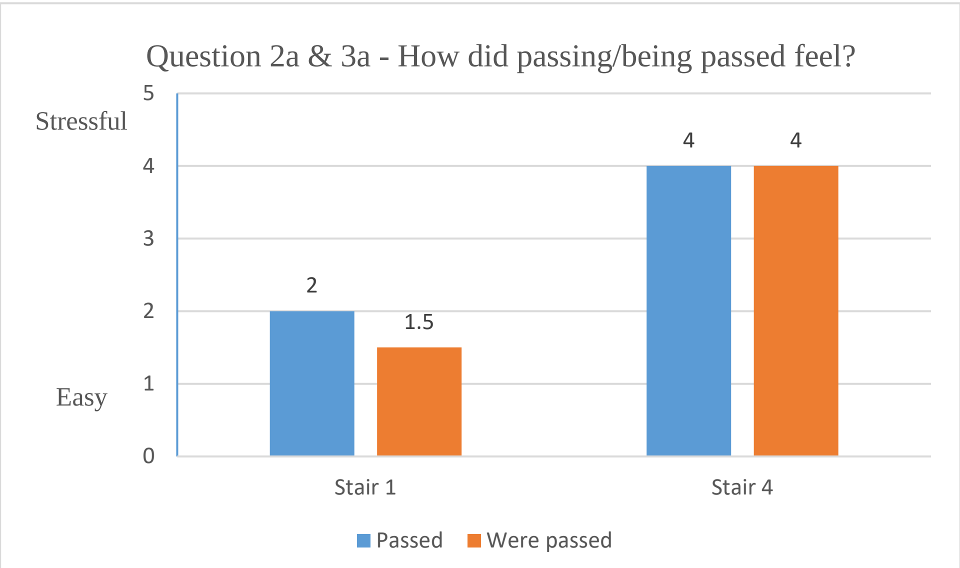


Figure 28. Representation of how the participants felt about passing/being passed.

Question 2b – If no, why not?

When asked why they did not pass, the participants give a variety of answers, see Figure 29. For all but Stairway 2, most participants say that they did not pass anyone because they did not need or get the chance to. However, in Stairway 2 the most common reason is that they did not dare or felt uneasy about it. Other reasons given by the participants' state that the stairs were too narrow, and that it was *"not possible to pass"*. These reasons are common for Stairway 2 and 3 but was also mentioned in Stairway 1.

A recurring comment made by several participants is that *"It would seem rude to pass"*. Other interesting comments include *"It would clearly be dangerous"*, made regarding Stairway 3, and *"Felt like the group was used to walking single file from previous stairs and kept pattern"*, made after using Stairway 4.

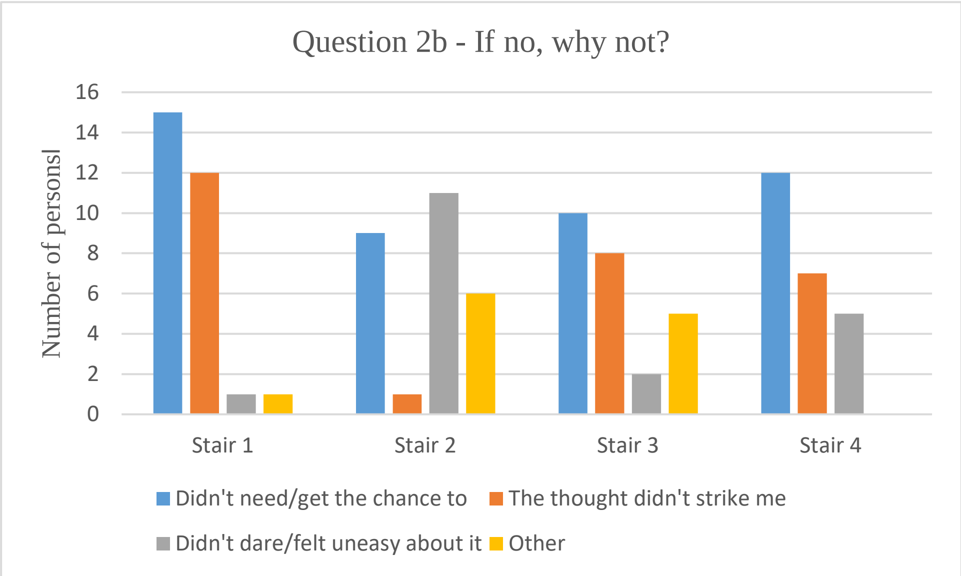


Figure 29. Reasons why most of the participants did not pass others.

6.5.3 Question 4 – How did you perceive the flow in the stair?

The perceived flow in each stairway is considered as relatively smooth, with Stairway 1 considered to have the smoothest flow, and Stairway 2 having the most cramped flow.

The overall perception of Stairway 1 is that it was easy and smooth and that *"You didn't have to think about safety"*, although one comment says that *"Some people have a slower walking pace, and made it flow worse"*.

Comments made about Stairway 2 again bring up that is it narrow and slow, but some participants do not see this as a negative: *"Although cramped, single file flowed well"*, and *"It flowed because we had to go one at a time due to tight space"*.

The flow in Stairway 3 is perceived as smooth, and that there was *"A definite consistent pattern"* in the stair. The stair is limited to single-file while still being *"Wide enough to walk comfortably without the added complexity of passing/walking alongside people"*.

Stairway 4, although wider than Stairway 3 is considered to have a more cramped flow. Several participants perceived the flow as cramped and comment that they did not like being able to hear and see other people's feet through the grated treads. Another comment was that the flow seemed cramped *"Due to the enclosing fence"*.

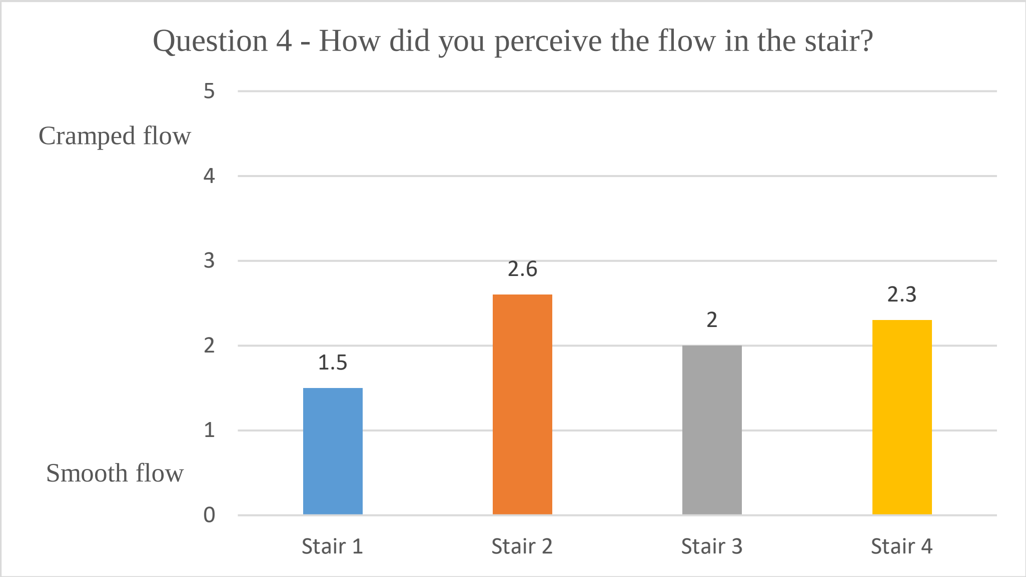


Figure 30. Representation of how the participants perceived the flow down the different stairways.

6.5.4 Question 5 – Did you ever feel uneasy/feel nausea?

Several participants felt uneasy when using the stairways, and a few experienced some nausea. Some claim that they might have felt uneasy or nausea if the stairways would have been higher. Nausea was only experienced in Stairway 2 and 4, where it was the length of Stairway 4 that contributed to the feeling.

The participants who felt uneasy in Stairway 3 comments that is because it was raining. In Stairway 2 the main reason was that the stairs move a lot, and are very creaky when used. The comments regarding Stairway 4 are centered around *"being able to see through the steps"*, and that the stairs were slippery due to rain.

All in all, almost a fourth of the participants felt either uneasy or nauseous using Stairway 2, and more than a third of the participants when using Stairway 4.

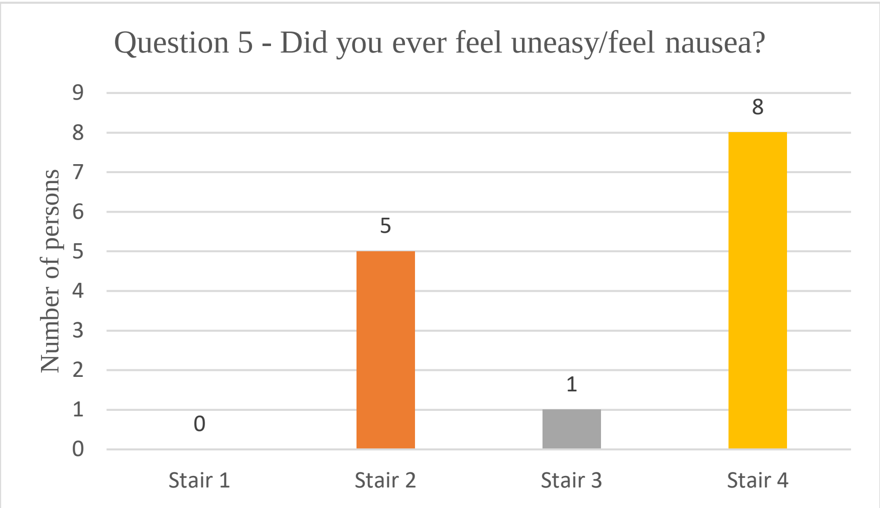


Figure 31. Number of participants who experienced nausea or felt uneasy when using the different stairways.

6.5.5 Question 6 – If you would compare the spiral stairs with a set of straight stairs, how would you describe them?

Most participants found all four stairways to be different when compared to straight stairways, see Figure 32.

Even though Stairway 1 is considered to have a smooth flow and be nice and wide, the fact remains that its tread depth varies depending on which part of the stair is being used. Many comments are made regarding the variable width and that *"You need to concentrate and watch your step"*, and one comment says *"Different speeds inside and outside make it different"*.

Apart from additional comments saying that Stairway 2 is narrow and cramped, a few comments regarding the stairway include *"Greater steepness"*, and *"More 'round' than 'down' in these stairs"*, due to the *"tightness of the spiral"*.

Not many comments were made about Stairway 3. One participant commented that *"You should always watch your steps"*, and another commented *"No breaks in the spiral, smooth flow"*.

Stairway 4 differs from the other stairways as it is longer, has frequent landings, is 'caged-in' and it is possible to see through the treads. These are all brought up in the comments made about the stairway. Some participants feel that the frequent landings make the stairway more similar, while others feel the opposite.

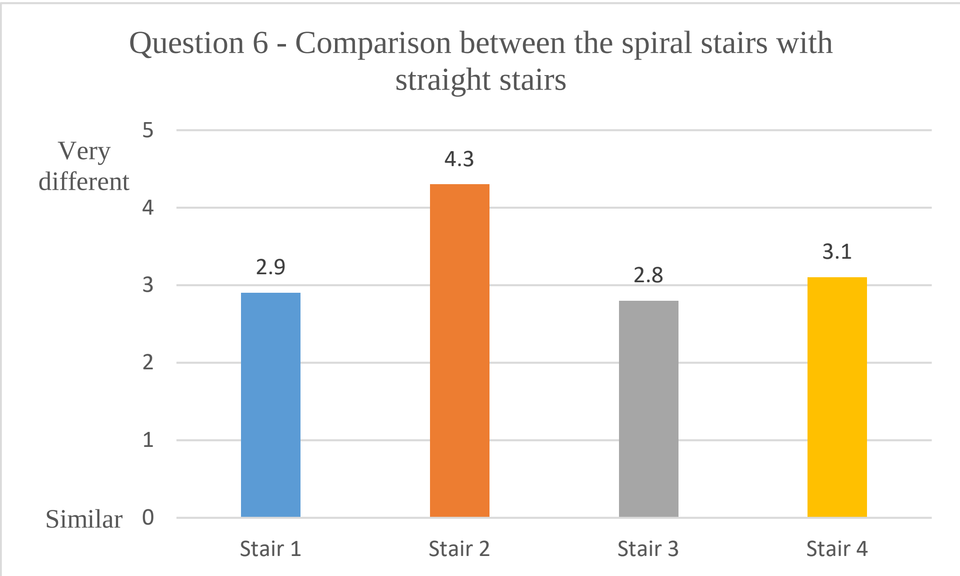


Figure 32. Comparison of the different stairways to regular straight stairs.

6.5.6 Question 7 – How did it feel using the spiral stairs compared to straight stairs?

In all cases but two was the experienced stress, flow and safety better in a straight stairway. The one exception being that Stairway 1 is thought to have a smoother flow when compared to straight stairways and that Stairway 3 is considered less stressful than regular straight stairs. In Stairway 1, 2 and 3 the variation in tread depth is commonly mentioned by participants as a contributor.

Interesting comments made about Stairway 1 is that it feels more cramped due to more people using it, as it allows more than single-file. Many participants thought that even though they must think more about where to put their feet the group moves more smoothly. Two participants contradict each other by commenting *"No risk of falling down a whole flight because corner interrupts fall"*, and *"Higher probability of falling down"*. Another participant does not like being unable to see past the curve of the stairs.

Again, many comments are made about how narrow and creaky Stairway 2 is, but there are also comments made saying that even though the stairs are narrow that they flowed well. One participant even states that the stairs feel safer due to being more constrained by the handrail.

Stairway 3 is considered to be less stressful to use compared with straight stairs. Two participants comment that the width only enables single-file, making for a similar or even less cramped feel. Another interesting comment says that *"Although the stairs were narrow it felt quite natural to move down them, also had more practice at spiral stairs by this point"*, which brings up the important point of familiarity of the stairs.

Comments about Stairway 4 are torn between the stair not being significantly different and that the build of the stairway makes for an uncomfortable descent. Two comments bring up the rain and the slippery surface, and an additional comment brings up the stress of being in a 'cage'.

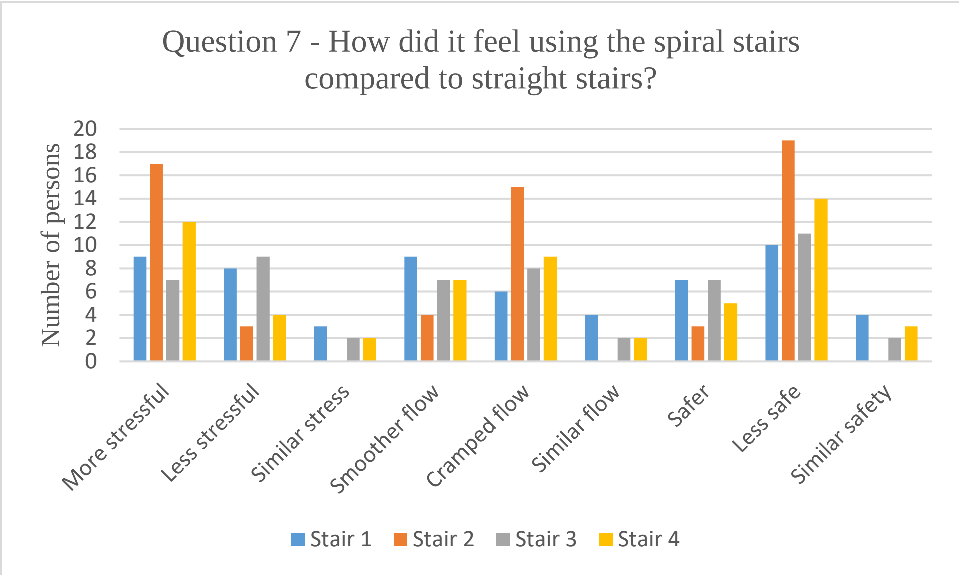


Figure 33. Comparison of the perceived safety/flow/stress of using each stairway compared to regular straight stairs.

6.5.7 Question 8 – Which parameter do you think has the biggest impact on the stairs' flow/safety?

When asked to rate (between 1-7, with 1 having the largest impact) how different parameters impact a stairways flow and safety, the results are as follow in Figure 41 below.

There are two parameters that appear are considered to have a larger impact than the rest, the width of the stairway and the tread depth. The riser, newel diameter and the presence of handrails are all considered to have a similar impact, with landing and curve of the stairway considered to have the least impact.

Two participants comment mentioning that the length and height of the stairway play an important role. Two other comments are made, saying *"If the stairs are wide enough for two people, flow is much less restricted"*, and *"To me the safety is best when the stair is narrow requiring single file"*. So, a wider stair is thought to better increase the flow of a stairway, but also make it more dangerous to use.

In the questionnaires, a few participants' express appreciation for the handrail. One comment notes that *"I held the handrail but realized that no one else did except when to start descent"*. This comment is made about Stairway 1 and implies that even if the stairs are nice and wide, an adjustment of gait is needed when transitioning from flat ground to a spiral stair.

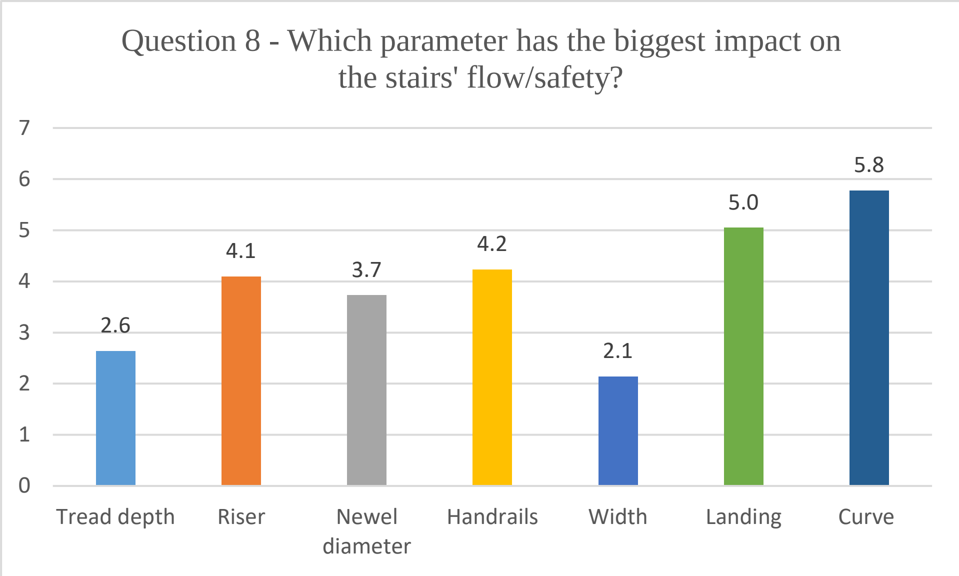


Figure 34. The perceived importance of the different parameters.

6.6 Analysis of videos

The videos that were recorded during the experiment are analyzed in the following chapter, and all noteworthy observations are presented below.

6.6.1 Stairway 1

The most notable observation made in Stairway 1 is the fact that the participants uses two lanes and walk side by side. A few individuals make their way down using the middle of the stair, which renders the individuals behind unable to pass on both the inside and outside. During test 1-2, all participants use either the inside or outside of the stairs which results in less congestion and the largest documented population flow. No passing is observed, as the participants walk with the same movement speed around the angle of rotation, and thus a constant flow is observed along the entire width of the stairs.

It is apparent that the movement speed is restricted by slower individuals, see Figure 35. This is most noticeable in Stairway 1, as the slower individual restricts movement in both the outer and inner parts of the stairs.

Figure 35. Gaps between slower and faster individuals.

Stairway 1 is the only stair on which there is a landing, apart from Stairway 4. One participant comments that it was of a smaller annoyance. It should be noted that the landing is subjected to congestion on a larger scale than the rest of the stairs, and the landing is at one point subjected to a population density of 3.1 persons/m^2, see Figure 36. This is most noticeable behind the slower individuals.

Figure 36. The landing in Stairway 1 was subjected to a higher population density than the rest of the stairs.

Another notable observation made in Stairway 1 is that in test 5 one participant is seen taking two steps on a single tread. It does not seem as though it is to adjust to the speed of the individual in front and indicates that the tread depth of the stairs is, for some persons, too large.

6.6.2 Stairway 2

The flow in Stairway 2 can be described as more uniform than in Stairway 1. The movement speed is less restricted by slower individuals and more restricted by the geometry of the stairway. As a result, there are no larger gaps between participants, as seen in Stairway 1 above. Many participants are seen holding the newel while descending the stairs, and looks as though most participants are taking caution when moving. The stairway is visibly shaking throughout the experiments.

6.6.3 Stairway 3

Stairway 3 is more similar to Stairway 2 as the flow looks to be more uniform than in Stairway 1. However, it is apparent that the movement speed is restricted by slower individuals more in Stairway 3 than Stairway 2. It is not in the same extent as in Stairway 1, which could be due to the participants being limited to moving in a single file behind one another. No one is seen holding the newel, and the participants look like they are moving with more confidence than in Stairway 2.

Figure 37. Difference between a uniform flow and a slower individual restricting movement behind them.

6.6.4 Stairway 4

Although having many differences to the other three stairways, the one that stands out in Stairway 4 is the length. Being much longer than the other stairways, the participants are able to find their gait, even though it proved difficult with the odd two treads then landing geometry of the stairway. The flow is more spread out in Stairway 4, with some individuals moving alone, and others in groups, see Figure 38.

The stairs are wide enough to walk side by side, but the participants generally move in a single file. One participant is seen trying to pass a slower individual, but fails, and ends up moving at a slower speed instead.

Figure 38. Flow in Stairway 4.

6.6.5 Summary

In all tests, the participants can be seen looking down at their feet. This is more apparent in Stairway 2 and 3, both of which are narrower than Stairway 1. Even so, not all participants made use of the handrails; a total of five used the handrails in Stairway 1 (three used the outer and two used the inner), a total of 19 used the handrail in Stairway 2 (eight participants used the newel as support), and five used the handrail in Stairway 3 (one participant used the newel). It is important to note that most participants do not grip the handrail, but hold their hand right above it. Passing is only observed in Stairway 4, but only by one participant. Passing is not observed in Stairway 1, although the participants generally moved side-by-side.

7 Discussion

7.1 Parameters and geometry

The parameters that were found to have the largest impact on the speed and flow down the different stairs are the tread and riser, the density and the width. An important observation during the experiment is that in Stairway 2 and 3, the geometry of the stairways played a more important role than the density. The movement was clearly restricted by the narrow width and angle of rotation around the newel, especially in Stairway 2, where the density and speed was almost constant for all the participants. With its solid build and slightly larger width, Stairway 3 allowed for a slightly larger variety in both density and speed, but the flow was still largely uniform. Stairway 1, however, proved to allow a wide spread of both speed and density. It is noted that in Stairway 1, the individual characteristics of the participants play a larger role in determining both speed and flow.

All the stairways, apart from Stairway 4, in the experiment have the height of one floor which might not be representative of what is expected in the event of an evacuation from a building. Stairway 2 and 3 each have quite restrictive geometry, which the occupant is affected by almost instantly as they enter the stairway. The width and tight angle of rotation cause the occupant to adjust their gait and speed quickly. Stairway 1 is wider and the angle of rotation is not as tight; the occupants can move quite freely for a while before they adjust to the stair and people around them. For a stairway like this, a longer test would be preferable to see if the movement of the occupants adjust to a certain pattern after a while or not.

Tread & Riser

The relationship between the tread and riser geometrically impacts the speed at which individuals move down the stairs. The outer tread used in Stairway 1 has a slope of 21°, which is in the 'uncomfortable' zone according to the NZBC. This tread recorded the highest speed which could be due to the tread depth being very large, forcing the participants to span an entire tread with each step. One participant was seen taking two steps on one tread, clearly affecting her gait. Even if this tread position recorded the highest movement speed, the tread depth in this case can be considered too large, and should not be recommended in spiral stair design.

Density

The density is generally calculated simply as the number of persons per unit area, and is an important parameter in crowd dynamics. The flow has generally centered around the density of a crowd in most research conducted on the subject. Stairs are different though, and researchers such as Thompson (1994) and Hoskins (2011) have discussed other methods of calculating and/or approximating density on stairs, both of which focus on the distance between individuals. In this report, the correlation between density and speed/flow is not great, but works rather well together with other parameters to be able to predict the average speed and flow down spiral stairs rather accurately.

An important observation is that the reported density in Stairway 2 is high, measuring 2.9 persons/m^2, yet the participants all keep at least one empty tread between themselves and the individual in front of them. According to Fruin, if the density on stairs reach 3.8 persons per square meter, no movement will occur. This assumption is the foundation of the speed and flow equations set out by Gwynne & Rosenbaum. The equation set out in this report use a similar assumption, but with a maximum density of 5.7 persons per square meter. The tread in spiral stairs becomes smaller closer to the newel, which might be the reason for this higher allowed density. It might also be an indication that a different method to calculate density on spiral stairs should be investigated.

Effective width

This report attempted to propose a new method to calculate the effective width of spiral stairs, since it became clear that the method for regular straight stairs cannot be applied. For the outside of the stair, the traditional effective width model will suffice, but the inner side of a spiral stair requires a larger boundary layer than the outer one due to the tread depth being smaller closer to the newel. The depth of the inner tread closest to the newel is also different from stairway to stairway. After a quick comparison with Pauls study which incorporated 58 office buildings, the three stairways in this report are not enough to accurately propose a method to determine the boundary layer. It is believed that the boundary layer is affected by the angle of each tread, the width of the stairs and the diameter of the newel.

Stairway 3 was 0.4 m wider than Stairway 2, but the participants used only 0.1 m more of the tread. This resulted in a slightly higher speed and flow. When compared to Stairway 1, the flow increases exponentially with the width, due to the extra lane being used. This brings to mind the traditional step function method of determining flow, where the stairs are divided into lanes, each with a specific flow. It is predicted that in a spiral stair which only allows for one lane to be used, the occupants will not use more than roughly 0.5 m of width, regardless of the total width of the stairs.

Landings

The design of Stairway 4 is quite different from the typical spiral stairway build, mainly due to the occurrence of a landing after every two treads. The results from the questionnaires revealed that many of the participants expressed discomfort regarding the landings, as they caused the need to constantly readjust the gait during the descent. One participant also commented that the landing in Stairway 1 was of a minor inconvenience because it disrupted the flow down the stairway. The occurrence of a landing every once in a while, may be welcomed by occupants, as the landing serves as short break from vertical travel or makes for the opportunity to pass others in front. However, future designers may want to be wary of the implication of having too many landings in their stairway.

Material

Stairway 1 and 3 are both constructed with concrete, and only one participant expressed the feeling of being uneasy when using Stairway 3 (none for Stairway 1). More participants were uneasy when using Stairway 2, and especially Stairway 4. The reason for Stairway 2 is that it is free standing and sways and creaks when it is used. For Stairway 4, the reason was mainly the fact that the stairway is built of grated steel. In the rain, the steel looked slippery which made a few participants uneasy. It was also that it is possible to see through the stairway to the occupants moving below and above, which can be distracting. More research might have to be done regarding how much this can impact the occupants of a stairway.

7.2 Individual behavior

In recent decades, the individual behavior of occupants on both level ground and on stairs is becoming subject to research. An average value of density, speed and flow are useful for quick calculations of the evacuation process, but for a deeper analysis and a more accurate calculation, individual occupants are required to behave individually, and therefore, more realistically. The two papers by Thompson and Hoskins both focus on this.

Inter-person distance/Number of open treads

Thompson brings up the idea of the inter-person distance and how it can be translated into density on level ground, which is adopted and altered for stairs by Frantzich, whereas Hoskins discusses the number of open treads between occupants in a stair.

On level ground, the classic method of measuring density is well suited, but is usually an average value for whichever area it is calculated for. The inter-person distance allows to calculate the density for an individual in a crowd, which can be considered a large step forward in crowd dynamic studies. In stairs, however, movement seems to be governed more by a specific individual; the one in front. During the descent in a stairway, occupants seem to be more concerned with the individual in front of than with the one around (given the width allows for multiple lanes), and to avoid stepping on the heels of the individual in front, adjust the distance accordingly. In Stairway 1, it was observed that in a few cases, a participant would use the tread directly behind the participant in front of them. This was not observed in the other stairways, where the participants kept at least one empty tread in front of them at all times. The larger tread depth in Stairway 1 is possibly the reason for this as it allows for participants to get a little closer without the risk of stepping on the heels of the person in front.

Considering that most occupants will cover the length of a tread with each step they take also indicates that the classic way of measuring density is not well suited in stairs; people are not able to shuffle and get as close to others as they can on level ground. Instead they would stop and wait for the next tread to become available to use and then take a full step instead of shuffling.

Passing

The act of passing is only possible in Stairway 1 and Stairway 4. Passing in the other stairways is restricted by the width. In Stairway 4, passing was easily observed as the participants moved in a single file. In Stairway 1 it was more difficult to know what is considered passing, with two lanes having formed. Still, the participants did not walk past people in the other lane, and the speed around the angle of rotation is constant in both lanes. Therefore, the flow can be assumed constant across the entire width of the stairs. For design purposes, it is still recommended to use the average tread (middle tread) for a more accurate value.

The middle tread in between the two lanes was used by several participants. This restricted the use of the tread as only one person could use that tread, whereas when participants used a specific lane, it allowed the other lane on the same tread to be used, thus increasing the efficiency of the stairs. This was seen in test 2, where no participant used the middle tread, resulting in the highest documented flow. If a slower moving individual used the middle tread, they risked slowing down the entire crowd behind them, whereas if this occurred in the inner or outer lane, they only slowed down the specific lane.

Newel impact

One of the objectives set forth in this report was to investigate how the newel impacts movement in spiral stairways. When it was found that the derived equations were not dependent on the newel, this objective became less important. An interesting question for future studies is; does a spiral stair converge to being a straight stair with a wide enough newel diameter? A large newel diameter allows the inner tread depth to be large. Combined with a narrow width, where the outer tread depth is not much larger than the inner tread depth, a spiral stair could maybe be considered straight. But this would require a rather large newel. Also, the newel might be able to be used to propose a method to determine the effective width in spiral stairways.

Stairway 1 has a newel diameter at 1.38 m, allowing the inner tread depth to be comfortable. However, the stairs are also wide, 1.42m, which increases the outer tread depth too much, as one participant needed two steps to get across it. This indicates that for design purposes, there needs to be a relation between not only the tread and the riser, but also between the tread and the width.

Another observation made on Stairway 1, which has a comfortable tread depth along the entire width, is that all the participants were found to be looking down at their feet during the entire descent. The variable tread depth requires the participants to constantly concentrate on where they are putting their foot. Although this may cause people to feel less safe, the increased concentration and awareness probably decreases the amount of accidents that occur. So even if the people using the spiral stairs are more worn out from having to concentrate during an evacuation, the risk of falling during the descent is likely less than on regular straight stairs, where it is easier to find a more natural gait due to the uniform layout of the treads. This corresponds well with the study made by Kvarnström (1977), and the study cited by Templer (1992), both of which state that less falls are recorded in spiral stairs than regular straight stairs.

7.3 Equations

The resulting equations of the thesis are similar to the ones presented in the SFPE Handbook by (Gwynne & Rosenbaum, 2008), but have a few differences. It is unfortunate that Gwynne & Rosenbaum do not present the method they use in which to calculate the k-values for different stairs. The method should be similar to the one used in this report, since they are both dependent on the tread and riser of the stairs. However, the method is similar to the one presented by Buchanan (2001), with the only difference being that the square root of the ratio of the tread and riser is multiplied by 0.86, instead of 0.80, as presented in this report. It is interesting that the equations presented in this report are dependent on the tread and riser and density, just like the equations for regular straight stairs. So, is movement in spiral stairs that different from movement in regular stairs?

The presented algebraic equations presented in this report assumes average values of density. Assuming a homogenous density is not conservative says Hoskins (2011); according to basic human movement principles, there are known subpopulations who descend stairs slower than others, and depending on the number of different subpopulations used to derive an equation, the results can be variable. This is an issue that the inter person distance looks to improve, as it approximates a density for each individual based on the people around them. But the density around an individual is a dynamic parameter, and is constantly changing, as is seen especially in Stairway 1, where slower moving individuals started out right behind others, who later got away from them creating a lower density in front of them. The congestion behind the slower moving individuals also caused a higher density right behind them.

This study has a wide variety of ages and gender, but lacked in the total number of participants. A larger sample size would have been preferable, as the results would have been more reliable. Considering that the study conducted by Kuligowski, et al (2015) had more than 5000 participants, the mere 25 in this study does seem small. Future studies on the subject should therefore aim for a larger sample size. Hoskins mentions another shortcoming of simple algebraic equations, which is that they only provide a single answer. This is good from a design perspective, however, which is the goal of this report.

Movement speed

Equation 14 calculates a movement speed that is near identical to the documented movement speed in each stairway. Values from Frantzich (1996) also correlate well with the equation, which strengthens the reliability of it. It is curious that Equation 14 produces a higher value for the movement speed in spiral stairs than the existing equations for straight stairways do. This contradicts Kvarnströms (1977) findings that state that movement is slower in spiral stairs. More studies should be conducted to evaluate this and to validate the equation, as is discussed below.

An important observation is that the movement speed in Stairway 1 is the highest of the stairways used in this report, and using Equation 14 to illustrate the linear correlation with the density it is found that the movement speed in spiral stairs is very close to or even higher than when using the calculation for straight stairs with similar dimensions. It is very important to note that the equations for straight stairways have been derived based on conservative assumptions regarding population density, and is based on a few different studies. Considering this and the fact that they were derived for design purposes, it might not be that surprising that the equation derived in this study produce higher values, since they have been derived based on an experimental model. It is also important to note that the Equation is based on density values between 1.3 and 2.9 persons per square meter and still needs to be validated for values outside this interval. This is very important, especially since the equation allows for a maximum density of 5.7 persons per square meter, which is well above the density in which crushing conditions occur in regular stairways. Like mentioned above, this could be because of the treads decreasing in size closer to the newel, allowing for a higher density, but it could also indicate the need of a different method when approximating density in spiral stairs.

Population flow

The proposed equation for calculating flow down spiral stairways generally generates a value that is a little lower than the documented value, but the correlation between the calculated values and the documented values is very good. The fundamental traffic equation is a great tool for designing evacuation routes, as it can be used for most connections; now it can be used for spiral stairways as well.

However, both the density and the width of the equation might need to see some small changes, as discussed earlier. The correlation between the observed used width and the flow is the most reliable one, but it also underestimates the flow more than if the effective width or total width is used. The observed used width does not seem to have a notable relationship to the actual width of the stairs, and a different method would be needed for each stairway. But only three stairways were included in the experiment, and if more data was available, a better correlation might be able to be found. The observed used width is also measured as the width of the stairs on which the participants put their feet, and maybe if the width was measured at the shoulder height of the participants, a better correlation can be found.

The density is the same as for the movement speed, and the same 'problems' are found for this equation.

Calculated tread

The calculated tread depth is solely dependent on the outer tread depth of the stairs. Having data for a stairway with an outer tread depth and a width as large as for Stairway 1 is very beneficial for this equation, as it has two lanes. The result of the calculated tread is similar to the middle tread that is used for speed and flow calculations. The equation does not take into account the different lanes however, which is a limitation of the equation. The spread of the outer tread depths and widths of the stairs used for the calculation indicates a good fit, since 0.60 m is the minimum allowed width for a stairway according to the building codes reviewed in this report, and not many stairways with a width larger than 1.42 m are thought to be designed.

Summary

The equations proposed in this report give slightly higher values compared with the equations proposed by Gwynne & Rosenbaum for regular straight stairways. This finding came as a surprise, as it was expected that movement would occur at a slower pace in spiral stairs based on previous work on the subject. The proposed equations do however produce reliable values that are almost identical to the measured values, with linear correlations that have high R^2-values between 0.75 and 0.85. The equations are therefore considered reliable.

A reason for the higher produced values could be that the equations in this study are derived based on an experimental model, compared to the equations for straight stairways which are based on a design method and will therefore produce generally lower values. Another reason could be that the equations allow for a higher density. It is curious, however, that the equations are so similar. So do people move differently in spiral stairways when compared to straight stairways? Or is this just a coincidence for the stairs used in this report?

A thought that has struck the authors mind but has not been confirmed is that people might move faster down spiral stairs due to the constant feeling of being ‘pushed’ toward the handrail when moving down. Combined with the added security of a handrail being present for support, people move at a high pace, especially in Stairway 1, where the tread depth was the largest.

Also, if a fall were to occur, the occupant would fall forward onto the handrail instead of tumbling down the stairs due to this force, making spiral stairs safer to use.

8 Conclusion

8.1 Purpose and objectives

The questions that this report set out to answer are:

- Can a hydraulic equation be derived for spiral stairways?
- Which parameters play an important role in determining movement speed and population flow in spiral stairways?

The answers are as follows:

Yes, a hydraulic equation can be derived for spiral stairways, and the parameters that play an important role in these equations are the tread, riser, population density and width of the stairway.

The equations are deemed to be accurate, and data from other studies have been used to validate the equations, but more data is needed to make sure that the equations are reliable. They should be used with care, as they assume homogenous values for the density, and provide average values for the movement speed of a crowd and flow for a stairway. Movement dynamics in a stairway are not that simple, and are impacted greatly by individual behavior. The equations are still useful for quick analysis and comparison of different stairways, and can be used for design purposes.

Considering the spread in width of the three stairways, the equations are appropriate for stairs of similar design and within the evaluated interval of density and width.

8.2 Future studies

Is movement down spiral stairs that different compared to regular straight stairs? Based on the equations proposed in this report; no. But more studies should be conducted to be able to draw more reliable conclusions. Specifically, straight stairs that have the same tread and riser dimensions as the spiral stairs have in the line of going should be compared, as well as stairs with the same width. Spiral stairs with different newel diameters should be included in the studies to see if the newel does affect the movement at all, or if it is in fact the tread and riser that plays the biggest part.

More studies should also be conducted to analyze the individual behavior of people using spiral stairs. The individual behavior of people has been documented on level ground by researchers like Thompson (1994), and on regular straight stairs by Hoskins (2011), but not on spiral stairs.

A final topic is the density measurement on spiral stairs and if a new method should be proposed or not. Should the number of empty treads between occupants be used when determining flow in spiral stairs or should the regular density measurement be used? The study should also evaluate the difference between stairs that have a single-file and stairs that have multiple-files that are being used by the occupants and at which width a single-file stair goes to being a double-file stair.

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Appendices

Appendix A – Questionnaires

Questionnaire – A Study on Movement Down Spiral Staircases

1. Are you

- ☐ Male
- ☐ Female

2. You are ____ years old.

3. You are ____ cm tall.

4. Do you consider yourself to be healthy?

- ☐ Yes
- ☐ No

If no, why not?

____

5. How would you rate your level of fitness on a scale from?

Not fit at all					Very fit
	1	2	3	4	5

6. Do you use prescriptive eyewear/glasses?

- ☐ Yes
- ☐ No

7. Are you

- ☐ Left-handed
- ☐ Right-handed
- ☐ Ambidextrous

TESTS – Stair 1

1. How did it feel moving down the stairs? Feel free to comment below if anything special struck you during the test.

Easy					Difficult
	1	2	3	4	5

Comments:

____

2. Did you pass anyone while moving down the stairs?

- ☐ Yes
- ☐ No

a) If yes, how was the experience/how did it feel?

Easy					Difficult
	1	2	3	4	5

Comments:

____

b) If no, why not?

- ☐ Didn’t need to/didn’t get the chance
- ☐ The thought didn’t strike me
- ☐ Didn’t dare/felt uneasy about it

- ☐ Other reason: ____

3. Did someone pass you on the while moving down the stairs?

- ☐ Yes
- ☐ No
- a) If yes, how was the experience/how did it feel?

Didn't faze me Stressful

1 2 3 4 5

Comments:

____

4. How did you perceive the flow in the stair?

Smooth Cramped

1 2 3 4 5

Comments:

____

5. Did you ever feel uneasy/feel nausea?

- ☐ Yes
- ☐ No

Comments:

____

6. If you would compare the spiral stairs with a set of straight stairs, how would you describe them?

Similar Very different

1 2 3 4 5

Comments:

____

7. How did it feel when using the spiral stairs compared to straight stairs? Circle the answer that best suits your experience in each line.

- ☐ More/less stressful
- ☐ More/less safe
- ☐ Smoother/more cramped flow

Comments:

____

TESTS – Stair 2

1. How did it feel moving down the stairs? Feel free to comment below if anything special struck you during the test.

Easy Difficult

1 2 3 4 5

Comments:

____

2. Did you pass anyone while moving down the stairs?

- ☐ Yes
- ☐ No

a) If yes, how was the experience/how did it feel?

Easy Difficult

1 2 3 4 5

Comments:

____

b) If no, why not?

- ☐ Didn't need to/didn't get the chance
- ☐ The thought didn't strike me
- ☐ Didn't dare/felt uneasy about it
- ☐ Other reason: ____

3. Did someone pass you on the while moving down the stairs?

- ☐ Yes
- ☐ No

If yes, how was the experience/how did it feel?

Didn't faze me Stressful

1 2 3 4 5

Comments:

____

4. How did you perceive the flow in the stair?

Smooth Cramped

1 2 3 4 5

Comments:

____

5. Did you ever feel uneasy/feel nausea?

- ☐ Yes
- ☐ No

Comments:

____

6. If you would compare the spiral stairs with a set of straight stairs, how would you describe them?

Similar Very different

1 2 3 4 5

Comments:

____

7. How did it feel when using the spiral stairs compared to straight stairs? Circle the answer that best suits your experience in each line.

- ☐ More/less stressful
- ☐ More/less safe
- ☐ Smoother/more cramped flow

Comments:

____

TESTS – Stair 3

1. How did it feel moving down the stairs? Feel free to comment below if anything special struck you during the test.

Easy Difficult

1 2 3 4 5

Comments:

____

2. Did you pass anyone while moving down the stairs?

- ☐ Yes
- ☐ No

a) If yes, how was the experience/how did it feel?

Easy Difficult

1 2 3 4 5

Comments:

____

b) If no, why not?

- ☐ Didn’t need to/didn’t get the chance
- ☐ The thought didn’t strike me
- ☐ Didn’t dare/felt uneasy about it
- ☐ Other reason: ____

3. Did someone pass you on the while moving down the stairs?

- ☐ Yes
- ☐ No

If yes, how was the experience/how did it feel?

Didn’t faze me Stressful

1 2 3 4 5

Comments:

____

4. How did you perceive the flow in the stair?

Smooth Cramped

1 2 3 4 5

Comments:

____

5. Did you ever feel uneasy/feel nausea?

- ☐ Yes
- ☐ No

Comments:

____

6. If you would compare the spiral stairs with a set of straight stairs, how would you describe them?

Similar Very different

1 2 3 4 5

Comments:

____

7. How did it feel when using the spiral stairs compared to straight stairs? Circle the answer that best suits your experience in each line.

- ☐ More/less stressful
- ☐ More/less safe
- ☐ Smoother/more cramped flow

Comments:

____

8. ***Answer only once and at the end of the day***. Which parameter did you think has the biggest impact on the stairs flow/safety?

Rank the parameters from 1 to 6, where 1 is considered having the biggest impact and 6 having the smallest.

- ☐ Depth of the steps
- ☐ Height of the steps
- ☐ Diameter of the center pillar
- ☐ Handrails
- ☐ Width of the steps
- ☐ Landing
- ☐ Curve of the stairway (clockwise/anti-clockwise)

Comments:

____

TESTS – Stair 4

1. How did it feel moving down the stairs? Feel free to comment below if anything special struck you during the test.

Easy					Difficult
1	2	3	4	5	

Comments:

____

2. Did you pass anyone while moving down the stairs?

- ☐ Yes
- ☐ No

a) If yes, how was the experience/how did it feel?

Easy					Difficult
1	2	3	4	5	

Comments:

____

b) If no, why not?

- ☐ Didn’t need to/didn’t get the chance
- ☐ The thought didn’t strike me
- ☐ Didn’t dare/felt uneasy about it
- ☐ Other reason: ____

3. Did someone pass you on the while moving down the stairs?

- ☐ Yes
- ☐ No

If yes, how was the experience/how did it feel?

Didn’t faze me Stressful

1 2 3 4 5

Comments:

___

4. How did you perceive the flow in the stair?

Smooth Cramped

1 2 3 4 5

Comments:

___

5. Did you ever feel uneasy/feel nausea?

- ☐ Yes
- ☐ No

Comments:

___

6. If you would compare the spiral stairs with a set of straight stairs, how would you describe them?

Similar Very
different

1 2 3 4 5

Comments:

___

7. How did it feel when using the spiral stairs compared to straight stairs? Circle the answer that best suits your experience in each line.

- ☐ More/less stressful
- ☐ More/less safe
- ☐ Smoother/more cramped flow

Comments:

___

Appendix B – Information for participants

Information for participants

First of all, thank you for choosing to participate in this study regarding movement down spiral staircases. The study will take place at 9 AM on THURSDAY the 17th of November at the University of Canterbury (see map below for precise location). The study will approximately take up to 3 or 4 hours, including breaks.

My name is Patrik Gustafsson and this study is part of the Bachelors' thesis 'A Study of Movement Down Spiral Staircases' and is the final project of a degree in Fire Protection Engineering at Lund University, Sweden. The project is in collaboration with both the company Olsson Fire & Risk and the University of Canterbury and aims to evaluate which parameters play an important role when determining the population flow in spiral stairs. If possible, a hydraulic equation will be derived that can be used in evacuation calculations in buildings and constructions. As a participant, you will be asked to make your way down four different spiral stairs that are located around campus, see map below.

1. The first two staircases that will be used are in College House on Waimairi Road.
2. The third staircase is located across campus outside the fine arts building.
3. If time allows, the fourth and final staircase will be used and is located outside the engineering building.

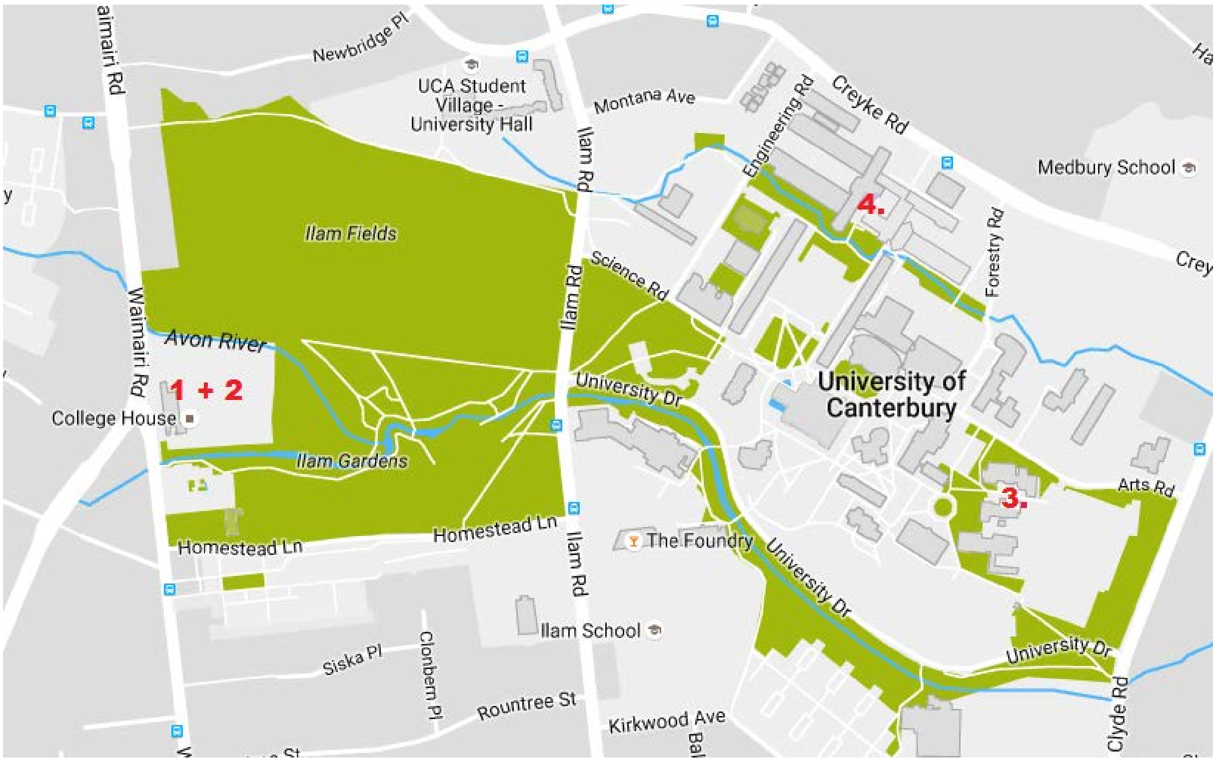


Figure 39. Map of where the stairs are located across campus.

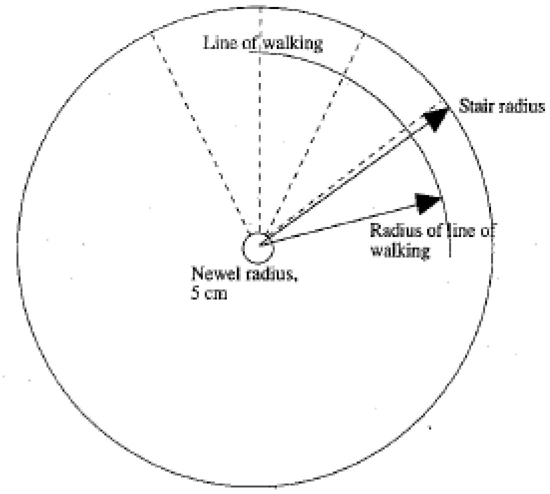
You will be asked to make your way down each stair once or twice as a group. The exception being the first staircase where three or four tests will be conducted down the staircase. After having completed the tests for staircases 1 and 2, we will walk together to the third staircase, and later to the fourth staircase. It will take roughly 15 minutes to walk between staircase 2 and 3, and additionally 6-7 minutes between stairs 3 and 4.

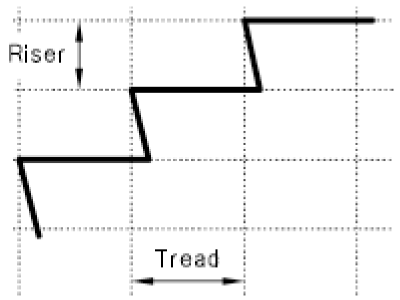
Snacks and coffee will be provided after tests have been conducted on the first staircase. Food will be provided after tests have been completed on the third staircase and will be served by the fourth staircase, outside if the weather allows.

I ask that you do not carry backpacks or purses down the stairs during the study. These can be placed in a suitable location by each stair, where me or one of my colleagues will be standing meaning that they will be under some supervision.

After the experiments, you will be asked to fill out a short, anonymous questionnaire regarding your experience when using each staircase. At the end of the day, you will receive a movie voucher as appreciation for participating in the study.

The two parameters that are of most interest in this study is the diameter of the center pillar (newel) and the width of the stair, see figure below. Two other parameters that are of interest are the depth of each step (tread) and the height of each step (riser).





Before the study begins, you are asked to read through and sign a consent form and a waiver of liability attached in this email. The forms will physically be available on Thursday.

If you have any questions, you can email me at patrik.gustafsson.835@student.lu.se

Again, thank you for choosing to participate in this study.

Kind regards,

Patrik Gustafsson