Evaluation of Undulations in Pedestrian Spaces and Their Effects on Walkability

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Abstract: Undulations in sidewalks result from the improper construction and improper maintenance especially in developing countries and negatively affect the walkability. Based on the observations of most frequently occurring undulations, 39 different cases excluding the control case were created in a simulated sidewalk. A set of participants were invited to walk along each of the simulated sidewalks and their walking speed, feeling of comfort and the walking behavior was observed. Results revealed that undulation depths 50mm, 70mm and 90mm are comfortable and 250mm, 350mm and 450mm are uncomfortable which identified from their behaviors.

Keywords - Undulations; Walkability; Sidewalk; Undulation length, Undulations depth, Pedestrian

1. INTRODUCTION

Walking is one of major parts of physical activity in the world. Promoting walking is the way to improve the physical activity level among the older adults (Corey L. Nagell; Nichole E. Carlson; Mark Bosworth; Yvonne L. Michael, 2008). Government and other organizations spend to encourage the people to use walking as a mode of transportation citing psychological, economical and health. Yet walking has received less attention due to poor walking infrastructure.

Some areas sidewalk is constructed purposefully due to the design needs of maintaining the levels of drains and to facilitate driveway crossing. Driveway crossings allow vehicles to cross the sidewalk and enter the street. Therefore, they consist of many of the same components found in curb ramps. It is the driver's responsibility to give way to the pedestrian at the driveway-sidewalk interface. Unfortunately, drivers are not always this sensible and pedestrians are put at risk. Sidewalks should offer a safe, comfortable while being attractive if people are to walk. In order to encourage the walking behavior it is important to clearly identify the impeding factors for walking.

The multitude of quality of life problems associated with declining walking rates has impelled researchers from various disciplines to identify factors related to this behavior change. To address this gap, Alfonzo (2005) had introduced a social-ecological model of walking that presents a dynamic, causal model of the decision-making process. Within the model, a hierarchy of walking needs operates and organizes five levels of needs hierarchically and presents them as antecedents within the walking decision-making process (Alfonzo, 2005).

An undulation is one of the factors affect comfort of walking. Especially undulations in side walk are barriers for the differently-abled. Different types of undulations can be found. In the Sri Lankan context the following undurations are observed.

- Purposely designed – These types of undulations can observe mostly in all classes of roads. This is done for the gate way entrance, entrance of road to the intersection etc.
- Drainage pattern – Drainage pattern makes an undulation in the sidewalk. Drainage level variations make these types of undulations which can be observed all over the country.
- Improper construction/design – These types of undulations mostly observe in C,D classes of roads. Improper survey, imperfection in surface finishing, etc are contributed to the improper construction's type undulations.
- Improper maintenance – This types identified in C,D classes or rural roads and make the level variations in the surface causes the undulations.
- Obstructions – Manholes, humps, root of trees etc are contribute to the undulations in sidewalk, specially occurs in C,D classes of roads.
- Geological conditions – These types of undulations available in hill country. Sidewalks are with longer undulations due to the locations.
- Settlements – Soil settlements contribute to the undulations due to the improper ground improvements.

The designers should be careful in designing walking areas having undulations. While some undulations are inevitable, it is important to understand how such undulations would affect the walking behaviour. Aim of this research is evaluate the effect of undulations in pedestrian spaces on walkability. Objectives are to investigate the effect of undulation length and undulation depth on ability to walk and understand the walking behavior of pedestrians up on encountering an undulation. Further optimizing pedestrian friendly undulation parameters to increase walkability by proposing a model for the design improvement and indentify the behavior of the pedestrians.

2. LITERATURE REVIEW

Walking has also become a focus for public health interventions because of its acceptability and accessibility, particularly among populations with a low prevalence of physical activity. (Siegel PR, Brackbill R, Heath G, 1995). Therefore, understanding environmental influences on walking activity is significant importance from a public health perspective (Fuzhong Li, K John Fisher, Ross C Brownson, Mark Bosworth, 2007). Public health strategies to promote physical activity or walking should emphasize the important role of environmental influences that facilitate opportunities and remove barriers for people to be more active (US Department of Health and Human Services, 1996). In this respect, findings from US DOH study suggest that neighborhoods containing high employment density and household density, more street intersections, and greater amounts of green and open spaces for recreation, are likely to increase urban mobility and be conducive to ''walkable'' neighborhoods. The results also suggest that each of these environmental characteristics contributes independently to neighborhood walking. In addition, the amount of variance explained by the combination of these neighborhood level variables also shows their collective contribution in explaining neighborhood to neighborhood variation in walking activity (Fuzhong Li, K John Fisher, Ross C Brownson, Mark Bosworth, 2007).

Walkability is defined as the extent to environment which built walking friendly and enabling pedestrian to move efficiently and safely around suburb spaces (Abley, 2007). Walkability considers condition of road way, walking comfort, safety, roughness, quality of pedestrian facilities. An irregularity in the road pavement surface is generally defined as pavement roughness which adversely affects the quality of a vehicle ride in the surface depth and end of length. A sidewalk is a path for pedestrians that are situated alongside a road. Concrete, asphalt, bricks and stones are usually use for the side walk construction in Sri Lanka. To enhance the pedestrian environment, a good sidewalk system is needed. Advantages of effective pedestrian environment are increasing mobility of pedestrians, more awareness of security and safety, aesthetic appeal, improved connections to transit and other transportation modes etc. The sidewalk corridor is part of the system of the pedestrian from the building edge to road way edge and generally parallel to street. Sidewalks designed for accommodating of people walk in alone or groups or with pets, for running, for skating, peaceful conversation, for playing and eating etc. Even though width of 45-60 centimeter is only need a person to walk alone but more space require for other pedestrians and purposes such as walking of couple, movement of wheelchair, pushing a cart or using a walker etc. In addition, sign posts, garbage bin, parking meters, post boxes, etc also can be at the side walk (Bloodlal, 2001).

However, the sidewalk grade should not go more than the grade of the adjacent street (Thibault, Lois E , 2003). The material on in the pedestrian environment which a person can wheel or walks is called surface. Difficulties of an area determine from the type of surface to negotiate. For example, for the movement of wheel chair users, gravel surface is impossible while most people traversed without more difficulties in wood floors (Federal Highway Administration, 2014). The sidewalk surface should be stable and relatively smooth yet not slippery, so as to provide proper traction (Gibbons, 1999). Sidewalk surface usability is affect by materials of surface, changes in level, slip resistance, firmness & stability, gap dimensions, openings and grades, visual and consistency. Minimizing the number of driveway crossings in a sidewalk significantly improves pedestrian safety (Designing site walk and trail access, Department of Transport U.S, 2014). Driveway crossings are often built with grade changes in the sidewalk corridor that have cross slopes greater than 2 percent. Driveway crossings should be designed with cross slope 2% maximum, level maneuvering space, changes in level 0.6mm maximum (flush) and flare slope 10% maximum (Designing site walk and trail access, Department of Transport U.S, 2014).

Sidewalk undulation is the level variation at walking surfaces which make uncomfortable to the pedestrian for their movement. It causes negative impact for pedestrians such as pedestrians with difficulty in their mobility by crutches and lifting feet, or certain ailments such as back problems, leg pains and becomes tired, pedestrian’s wheel chairs cannot climb over due to small front caster wheels spin sideways, in large change in elevation, pedestrian’s wheel chairs get difficult to roll, disable persons face difficulties (Paula Alexandra Sepúlveda Ferreira Da Silva, 2008) and decrease the comfort of walking spaces which may ultimately walkability. Causes of level changes are tree roots pushing upwards, uneven transitions from street to gutter to ramp, heaving and settling due to frost, buckling due to improper sub-base preparation, purposely design for drainage or gateways, improper maintenance and construction.

Most undulations are a result of poor maintenance. Some changes in level, such as a lip at the bottom of a curb ramp, are no longer recommended as a detection of the street ending and the sidewalk beginning. In rural roads improper constructions are mostly observed. While doing the constructions they don’t get the correct level and constructed in an improper ways.

Geologically some undulations observed in hill countries. And as mentioned above settlements and causes of obstruction in side walk also causes the undulations.

The purpose of undulation measurement study is to reveal the critical undulation wavelengths for various roadway categories and to suggest the most appropriate straightedge to control pavement smoothness and a straightedge normally associates various gains for profiles with different wavelength (Chen-Ming Kuo, 2012). As shown in Figure 1, If take the independent surface with the undulations Total length (L), undulation length (U_L) and undulation depth (U_d) are the identified undulation parameters which are contribute to make an impact on walkability.

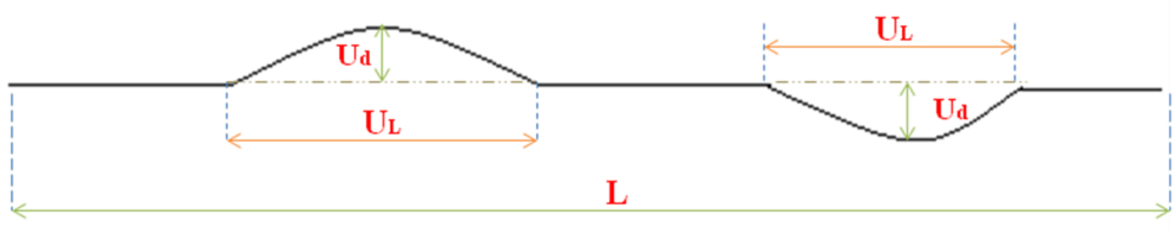

Figure 1.Undulation parameters used for the research

So here sidewalk characteristics and undulations have been reviewed and walkability of pedestrians is highlighted. So the effect of undulation in pedestrian spaces on walkability has been studied. Therefore effect of undulation parameters on ability to walk and pedestrian behaviors can be analyzed and discussed.

3. METHODOLOGY

3.1. Experimental Setup

Different types of undulations were observed and measured using rod and level survey method and their cross sections were plotted to study the variation of undulation parameters such as undulation length and undulation depth and identify the maximum and minimum undulation parameters. Similar walking surface has prepared at Faculty of Engineering of Sri Lanka Institute of Information Technology in different undulation length and different undulation depths according to the real cases from the observations. The following Figure 2 and Figure 3 shows the plan view of the side walk and cross section view of the prepared site walk surface respectively.

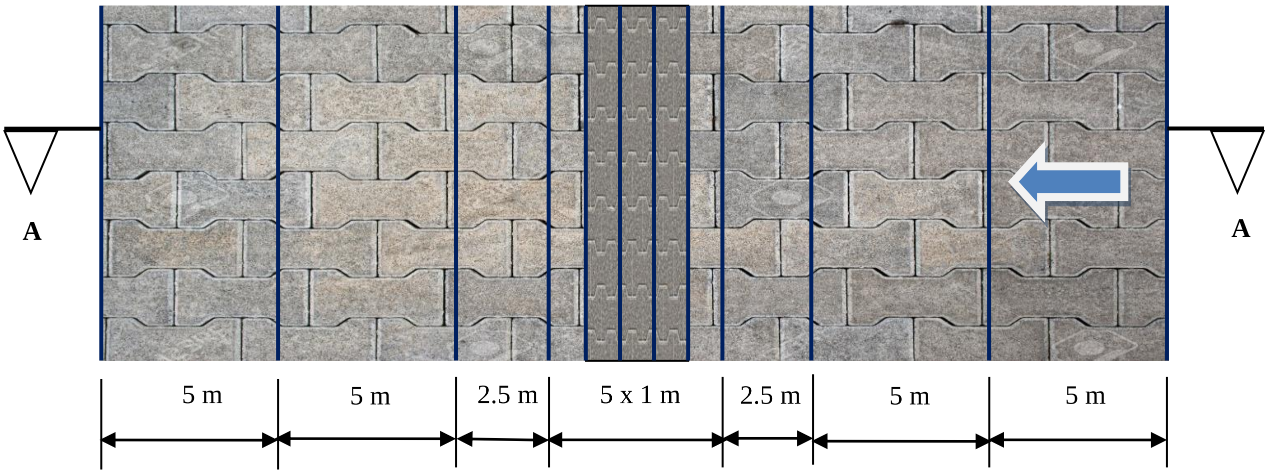

Figure 2.Plan view of the surface with grid lines

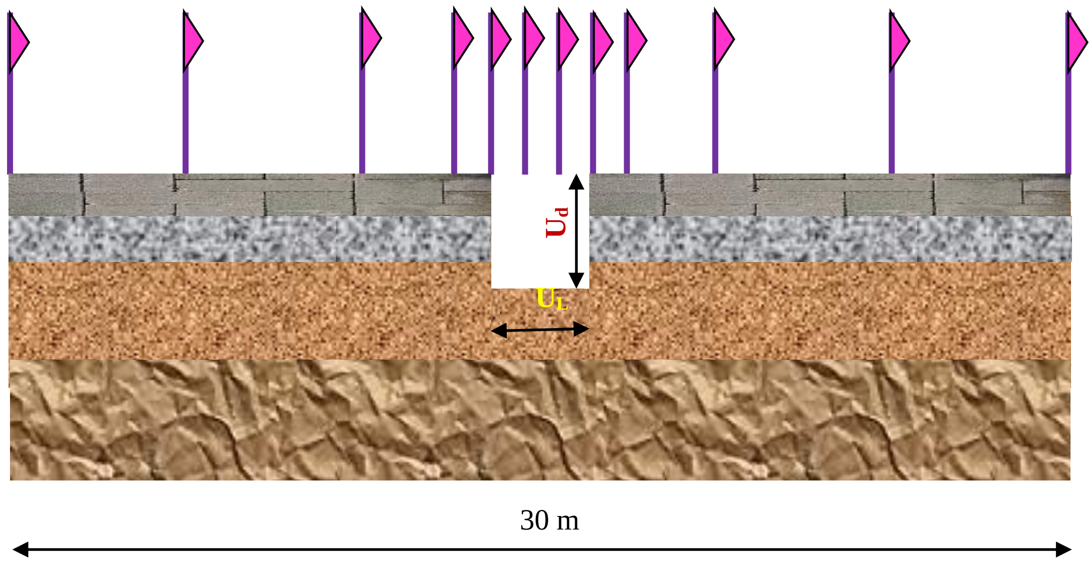

Figure 3.Cross section view (A - A) of the simulated walking surface

Combined of undulation length and undulation depth was categorized under 39 different cases. Table 1 shows the simulated cases for the experiment. In addition a case without any undulation was also prepared and used for experiment. 30 University students who volunteered participated in the experiment by participating each of the 39 cases and the undulated case. The cases were prepared in a random order. At a given time one case was simulated and all the participants participated in that case after which the next case was prepared. Practice session was done to bring the real scenario to the participants to reduce the learning curve effects. After the practice session the participant was asked to walk in the simulated walking space belonging to a particular case of undulation. His or her walking behavior was recorded in camera to identify their walking behavior on undulations and to extract walking time passing different grid points. These recordings were used to further study walking speed and walking behavior. In addition each participants were asked to rate the comfort of walking space.

Table 1.Simulated cases

Undulation length (m)	Undulation depth (mm)
0.5	50,70,90,120,150,200,250,350,450
1	50,90,120,150,250,450
1.5	50,70,90,120,150,200,250,350,450
2	50,90,120,150,250,450
3	50,70,90,120,150,200,250,350,450

3.2 Data

From the recorded videos, walking time extracted between every grid to calculate walking speed between the grids. After that walking stabilized point was identified and average speed of the walking was calculated. Number of steps within the undulated area taken from the video analysis and observed the relationship with speed variations and manipulation of undulation by stepping down the number of steps. Perceived comfort based on Likert scale was taken during the experiment to check the comfort of pedestrians when face the undulation parameters. Likert comfort scale which is used for the experiment. For each case of undulation the walking speed values of 30 participants were obtained. For each case the speed values of each case was compared with speed values of non undulation case by checking for the difference in mean statistically. Similar analysis was done for comfort values.

4. Results and Disussion

4.1. Approach to Analysis – Tests for the significant difference of mean between the case without undulations against undulated cases

For each 40 cases (39 undulated cases and the non undulated case) the comfort index and walking speed values were obtained for 30 participants. Figure 4 shows the mean values of comfort index for each undulation case and non undulation case and Figure 5 shows the mean values of speed for each undulation case and non undulation case. The effect of each undulation was studied by checking for the significant difference in mean between the particular undulation case as against non undulated case by conducting the t-test for the significant difference in mean. All the significance values for the difference in mean were below 0.000 for both comfort index and walking speed. This confirms that each of these undulation significantly affect comfort and walking speed.

4.2. Approach to Analysis

Maximum undulation depth was measured as 370 mm and undulation length was 1.3m. The variation of Perceived comfort across different undulation length and undulation length is shown in Figure 4.

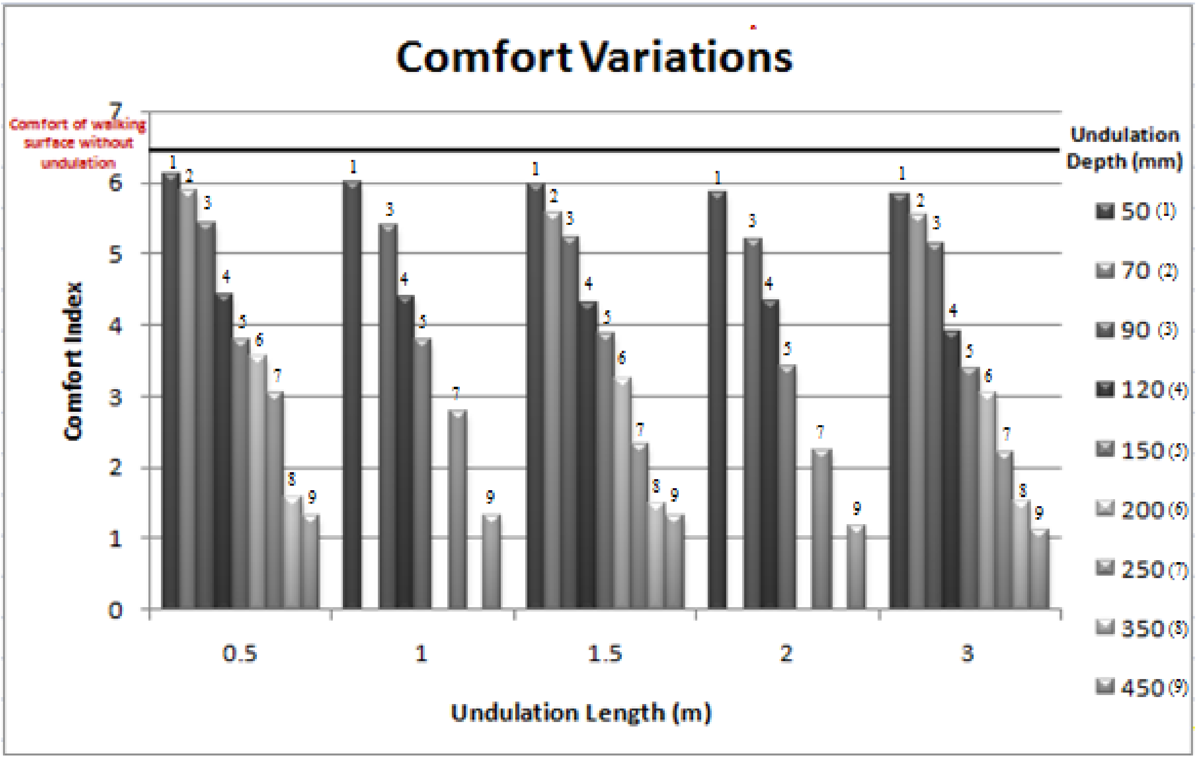

Figure 4. Comfort variation across different undulations

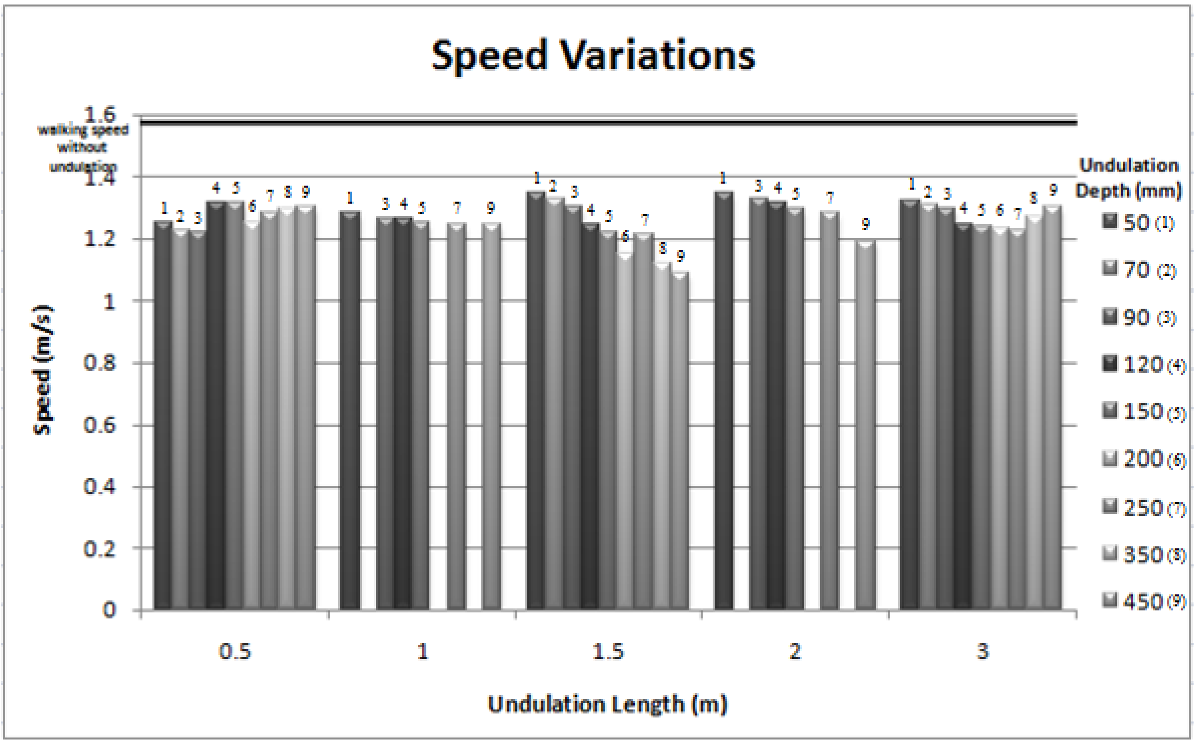

Figure 5. Speed variation across different undulations

Speed of the pedestrians is the main factor to observe the walkability of the pedestrians. Above Figure 5 shows the effect of undulation length and undulation depth in walking speed. Numbers of steps in the undulated area of the pedestrians are varying according to the undulations length which is shown in Figure 6.

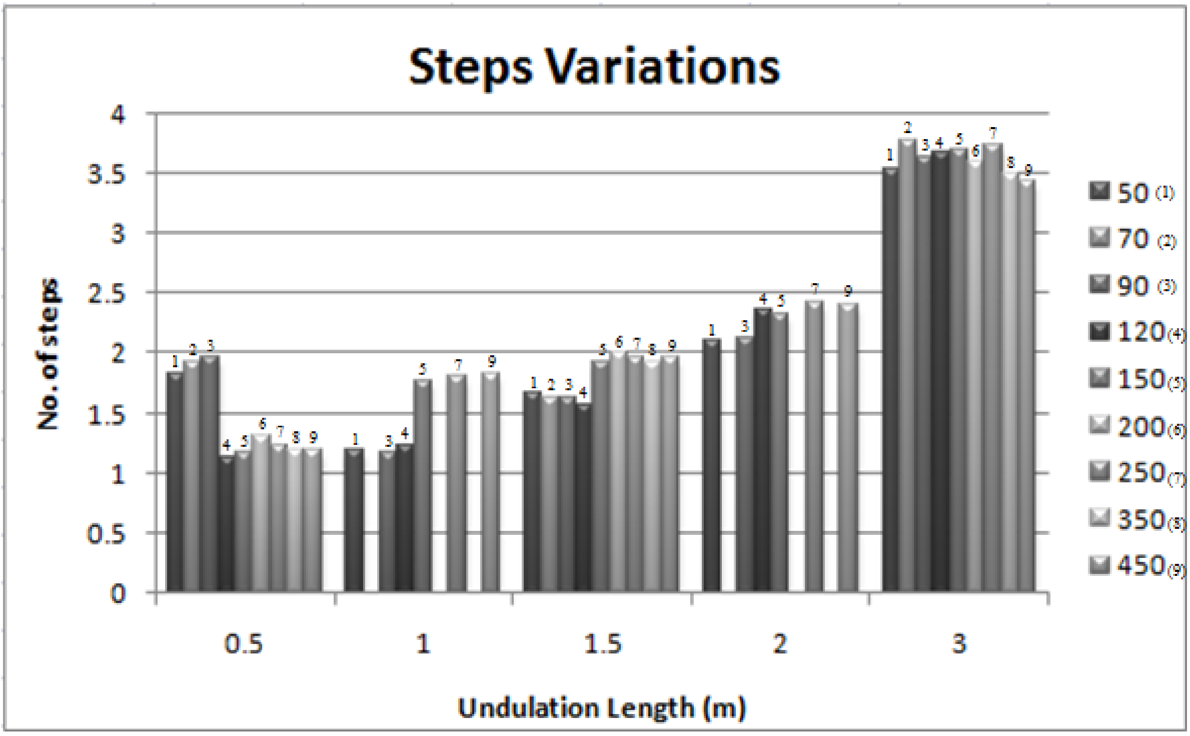

Figure 6. Variation of number of steps across different undulations

4.3. Discussions

Significance of this research is optimizing pedestrian friendly undulation parameters to increase walkability by proposing a model for the design improvement and identify the behavior of the pedestrians. This research was done in systematically variation method. Natural walking environment was prepared and actual walking behavior was observed along with perceived preference to walk.

Effect of undulation length and depth on comfort

Figure 4 shows the variation of the comfort with undulation length and undulation depth. Accordingly the comfort decreases with the increase in undulation length and undulation depth. In observing the highest undulation depths 250mm, 350mm and 450mm were found out to have lower comfort indices in the range of discomfort. Increase in undulation depths gives uncomfortable and dislike to the pedestrians to step down and go through it. So they are looking for an alternative ways to pass it and higher undulation depths were given lower comfort indices. In same manner, if consider the less undulation depth such as 50mm, 70mm and 90mm have a comfort index in comfortable zone. So the pedestrians like the less undulation depths and psychologically fit to go through it. The remaining cases are in a range of neither uncomfortable nor comfortable.

The increase of undulation depth leads to decrease of comfort. Undulation depth 200mm of undulation length 0.5m has comfort index of 3.57 and Undulation depth 200mm of undulation length 3m has comfort index of 3.03 due to the increase of undulation length in an independent walking surface.

Effect of undulation length and depth on walking speed

Walking speed is an indicator or walkability. It depends on undulation parameters. According to the comfort variation pedestrians feels comfort in low undulation depth. Therefore speed should be comparatively high in lower undulation depths. If consider the 350mm and 450mm undulation depth of 3m undulation length, shows the sudden increase in its speed. Similarly if go through the 0.5m undulation length it shows the different variation apart of other undulation depth in same undulation length. It's most likely to increase the speed with increase of undulation depth. Even this undulation length is jumpable. So that speed variation in undulation length of 0.5m is showing the unfair deviations with all undulation depth it has. So from this correlation analysis it can clearly understand the pedestrian's behavior and their response to the undulation parameters. Further their speed has a sudden reduction when they walk very close to the undulated area especially for the highest undulations depth; they take some time to prepare themselves to step down in the undulations. Following Table 2 shows it clearly.

Table 2. Average speed for some selected cases

	Immediately before undulation	In the undulation	immediately at increase of undulation climb up
Case 15	1.06 ms-1	-	1.08 ms-1
Case 30	0.92 ms-1	1.08 ms-1	0.93 ms-1
Case 39	0.95 ms-1	1.25 ms-1	1.00 ms-1

From the above Table 2 it shows that pedestrians speed in walk is getting reduced before they step down the undulation. Then their speed is little rise up in the undulated area and again getting some reduction when they climb for the regular surface which comparatively little higher than speed just before the undulations. This behavior of pedestrians is observed mostly at higher undulation depth like 250mm, 350mm and 450mm.

Effect of undulation length and depth on walking behavior across undulations in terms of number of steps

Number of steps in the undulated areas is one of the factors to judge the speed variations. The need of these steps data in this research is to identify the pedestrian's behavior and discuss the speed variations citing the steps variation. There is a hidden relationship with speed and behavior of stepping down in the undulated area. Number of steps in undulation is not varying uniformly. But average number of steps is increasing with increases of undulation length. It can observe that numbers of steps are less in highest undulation depth compare with other depths in a same undulation length 0.5m and 3m. But highest numbers of steps were recorded in highest depths for rest of other undulation lengths such as 1m, 1.5m and 2m. So here pedestrian's behavior for the undulations is clearly observed. Number of steps in the undulated area is less means, the number of pedestrians went through the undulation area is less. This behavior shows their dislike of undulations. They feel their walkability is affecting by it. Therefore they go for an alternative to cross it if available.

While crossing the smallest undulation length 0.5m, most of the pedestrians are not like to step down and they jumped over the undulated area for the worst undulation depths. But in smallest undulation depth such as 50mm, 70mm and 90mm, they stepped down and went through it and it shows their comfort here. But for the intermediate cases like undulation length of 1m, 1.5m and 2m shows the inverse of it. Because intermediate undulation lengths fairly long and not suitable to jump over it. So pedestrians step down and pass the undulations. Even the longest undulation length 3m is also not safe to jump. But compare with intermediate lengths, these shows more uncomfortable as discussed under comfort variations and make the people to think for discovering an alternative way to pass the highest depth of undulation. Therefore most of the pedestrians try their best to use the alternative way if available around the undulated area. Because of these number of steps shows the disorder in variation. Further steps variations are resulting effect on speed variation. Obvious truth is speed reduces with more number of steps. If the number of steps in the undulation is high, it means pedestrians slow their speed and take some time to pass it.

5. CONCLUSION

This research intended to evaluate the effect of undulation length and depth on walking behavior namely on perceived comfort and walking speed. Perceived comfort was found to decrease with the increase of both undulation length and undulation parameters. Walking style and pedestrian's behavior to the undulations make changes in walking speed or walkability. Analysis of video recordings showed that up on encountering undulations pedestrians would jump over undulated area or change the walking path for the maximum undulation depths more than 150mm. Comfort model is calibrated with the ideal comfort index and it is divided into three major parts for evaluate it. This study helps to identify and judge the pedestrian spaces in order to provide better walking environment to increase the walkability of the pedestrians.

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