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Article

Measurement of Construction Workers' Feeling by Virtual Environment (VE) Technology for Guardrail Design in High-Rise Building Construction Projects

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Abstract. According to the information of accidents, fall from height makes the highest death of construction workers. Nowadays, the design standards of fall protection system, e.g., guardrail have not considered workers' feelings. However, workers' feelings such as safety feeling and convenient feeling may affect safety and productivity of construction workers. The objective of this paper is to propose a construction workers' feeling measurement by feeling measurement tools used for guardrail design in high-rise building construction projects. The three types of the tool were developed for construction workers' feeling measurement, such as 2-D of construction project environment included dimension and characteristics of guardrails 2-D pictures with dimension of guardrails related to workers' dimension, and Virtual Reality (VR) models run in Virtual Environment (VE) equipment called CAVE. The standard deviation (*S.D.*) and Coefficient of Variation (*C.V.*) of workers' feelings were used to indicate the performance of workers' feeling measurement tools. Moreover, in the case study, the most effective tool was applied to measure the workers' feelings in order to design the guardrail by considering not only cost of guardrail, but also construction workers' feelings. The suitable guardrail was analyzed by Analytic Hierarchy Process (AHP) method. The results of construction workers' feeling measurement by the three types of the tool showed that for guardrail design, workers' feeling measurement by VR models in CAVE is the most effective tool compared with others. From the result of the case study, it showed that the suitable types of guardrail can be designed by considering both cost of guardrail and construction workers' feelings.

Keywords: Workers, safety, guardrail, high-rise building, virtual environment (VE).

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1. Introduction

1.1. Background

In Thailand, occurrence frequency of accidents in the construction industry is high when it is compared with other industries because of its characteristic of works [1]. The main cause of accidents that makes high impact to workers' death and injury is falling from height [2]. The effects of accidents can be classified into two damages, such as direct damage, e.g. workers' death and injury and indirect damage, e.g. stop of working and project image [3]. Generally, in a high-rise building construction project, safety systems were designed not only by following safety design standards, but also saving cost. However, it was not designed for following construction workers' feelings during construction activities. Problems of worker whose workplaces were in the high level zone in a high-rise building construction project are such as having not enough quality of protection systems, e.g. guardrail. They may feel as though working in a dangerous zone that may influence on their behaviors and affect production rate. Also, using over design of protection system may influence on workers' convenience during works that can affect their production rate. Thus, designer should design protection system by not only by following design standard and saving cost, but also considering workers' feelings such as, design of fall protection system, e.g. design of guardrails in a high rise building construction project. However, the problem is how to measure the workers' feelings. For measurement of workers' feelings, they should be able to recognize and respond to their feeling, e.g. some dangerous situations in their works. Consequently, it requires an effective tool that can be applied to measure workers' feelings in order to design fall protection equipment, such as guardrails. Therefore, the objectives of this research are to verify the performance of workers' feeling measurement tools by comparing the variation of workers' feelings when they were tested their feelings by the tools, and to propose a case study of fall protection equipment (guardrails) design in the high-rise building construction project by considering construction workers' feelings.

1.2. Factors Influencing on Workers' Behaviors

Two main factors that influence on workers' behaviors and their productivity were described by Masingboon [4]. The first main factor is a personal factor or individual factor that influences on working behaviors which consist of two miner factors, such as internal personal factors, e.g. skill, motivation, trust, and popularity, and external personal factors influencing on workers' abilities, e.g. experience, training, and education. The second main factor is a situation factor that refers to environment conditions that influence on workers' abilities which are classified into two miner factors, such as work physical, e.g. methods of work, working environment, conditions of works, and social factors, e.g. organizations. Due to [4], a working zone in a high level area is an important working environment in a high rise building construction project that directly influence on workers' behaviors and productivity. Furthermore, performance of humans' senses such as visualization, taste, listening, and touching were studied by Muira et. al. [5]. The result showed that visualization is the highest performance sense to recognize dangerous situations. Especially, people who work in a high level area may have feeling, such as scare, lack of confidence, and decreasing their abilities to make a decision that influence on their work performance. Workers' fatigue from construction works, e.g. scaffolding and formwork in a high rise building construction will affect to their safety feelings [6]

1.3. Design Standard of Fall Protection Equipment

Currently, design standard of safety specified to use fall protection equipment for working areas above 6 feet (1.8 meters) high [7]. The standard proposed three types of the fall protection system such as guardrail system, safety net system, and personal fall protection system. However, the format of those protection systems is not specified, including type and size of structures, spacing of structural members, etc. The user or designer will design it by using the local standard based on workers' characteristics in each country. In Thailand, [8] has specified minimum height of a guardrail for the fall protection is not lower than 0.90 meter. However, it has not specified the format of guardrail structures which depends on designers' perceptions. Fall protection hierarchy was described that it must be used when choosing methods to eliminate controlling of fall hazards. The steps are listed in the order in which they should be considered, such as guardrails, fall restraint, fall arrest, and work procedures, respectively [9].

2. Design of Guardrails in High Rise Building Construction Projects

Johnson et al. [10] presented the design of fall protection systems for roofing work, e.g. a guardrail, a safety net, and personal protection tools. In this research, several types of the guardrail were designed by following the design standard from the literature reviews and the practical format from construction site surveying of high rise building construction projects in Bangkok Metropolis, Thailand, respectively. From the literature reviews and construction site surveying, it was found that around six types of the guardrail were applied in the practical construction as follows:

First guardrail type (Type I) is a double-rail with 0.45 meters spacing and 0.90 meters high. The second one (Type II) is a double-rail with 0.60 meters spacing and 1.20 meters high. The third type is a triple-rail with 0.30 meters spacing and 0.90 meters high. The fourth type (Type IV) is a guardrail which installed four rails with 0.30 spacing and 1.20 meters high. The fifth type (Type V) and the sixth type (Type VI) are net type that use steel net 0.25 meters spacing with 0.90 meters and 1.20 meters high, respectively. The six types of the guardrail are shown in Fig. 1.

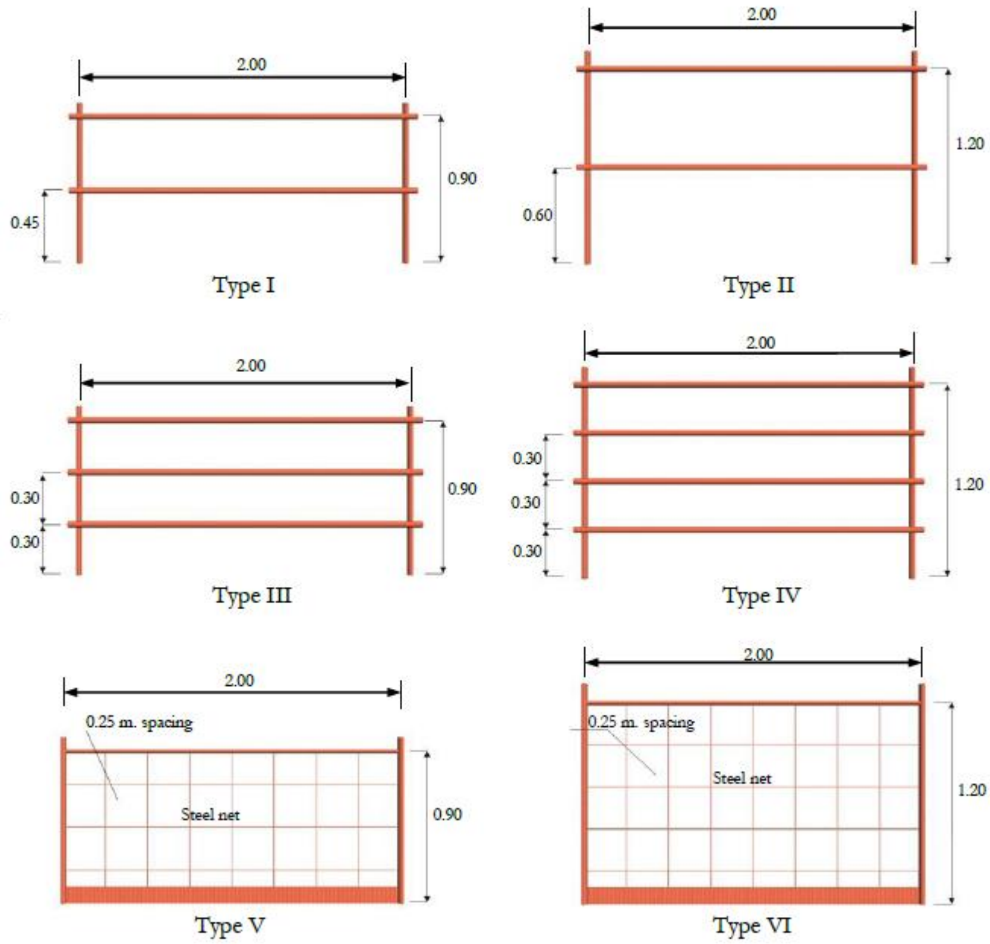


Fig. 1. The six types of the guardrail designed by following the design standard and practical construction.

3. Experimental Efficiency of Workers' Feeling Measurement Tools

From the study of [5], visualization is the sense that has higher performance to recognize the environmental situation than the others. In this research, the workers recognized their working environment by using their visualization sense. Therefore, it needs the visual tool that has high performance to reflex workers' feelings in their working environment. For workers' feeling measurement, the workers should feel as if they were working in a real situation and environment [11]. The methodologies that were used to verify the efficiency or performance of workers' feeling measurement tools can be described as follows:

3.1. Developing Construction Workers' Feeling Measurement Tools

In this research, the 3 types of workers' feeling measurement tools were applied to measure the construction workers' feelings. The feeling measurement tool Type I is 2-D pictures of guardrail with its dimension as shown in Fig. 1 that printed on paper. The tool Type II is 2-D pictures of guardrail with the true-scaled worker's picture that printed on the paper, and the tool Type III is VR models of guardrail that run in Virtual Environment (VE) equipment called "CAVE" as shown in Fig. 2 and Fig. 3, respectively. The details of each feeling measurement tool are described as follows.

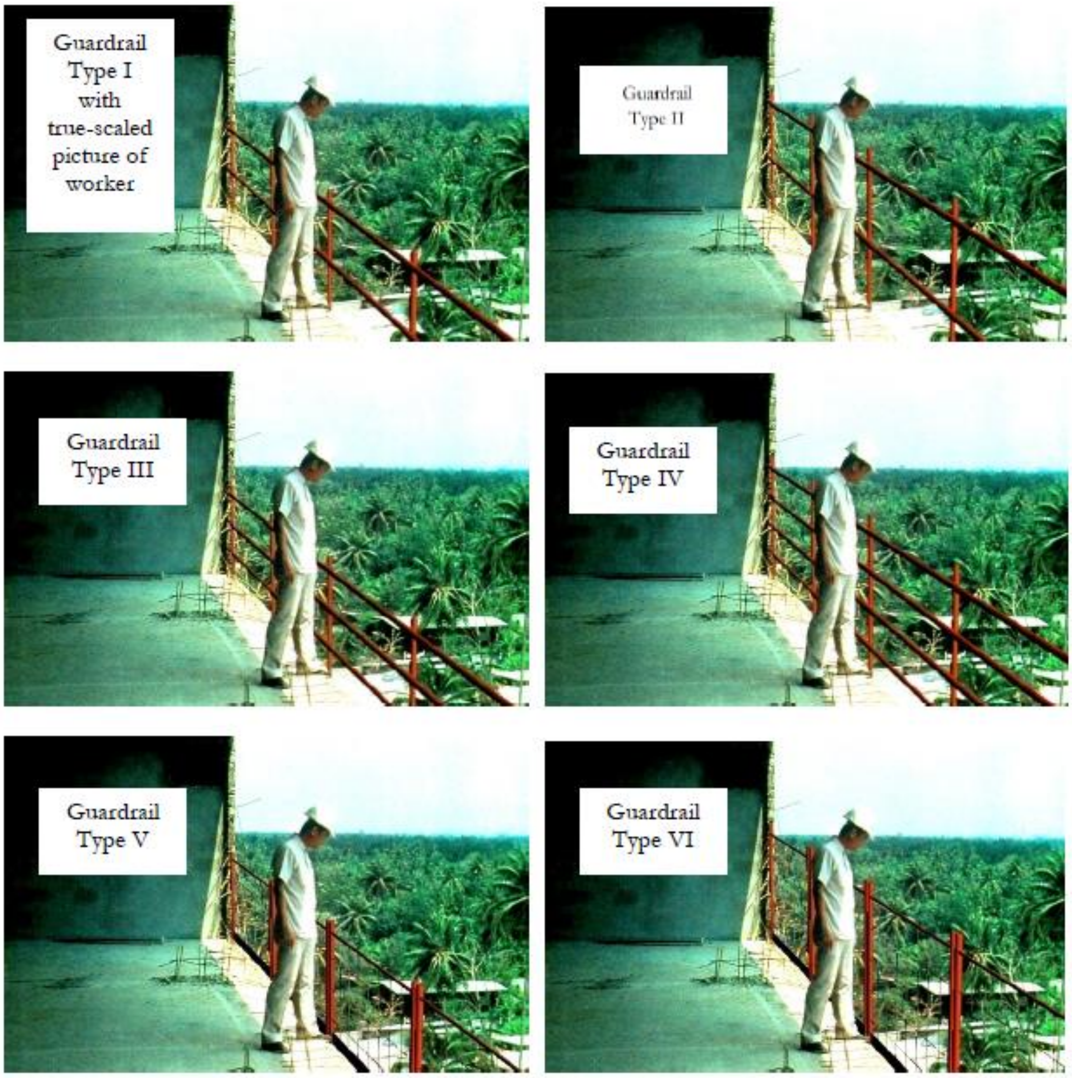


Fig. 2. The 2-D pictures of six guardrail types inserted with the true-scale workers' picture (Modified from [12]).

3.1.1. The two-dimension (2-D) pictures of guardrail printed on the paper

The first feeling measurement tool (Type I) is 2-D color pictures of guardrail model which were printed by a color printer. One picture illustrates one type of the guardrails with its component and dimension, such as width, height, and rail spacing. The six types of the guardrail picture as shown in Fig. 1 were printed into some hardcopy paper and used to measure workers' feelings. The construction workers were randomly selected to use their visual sense by looking at those guardrail pictures and responding their feelings in term of safety and convenience as though they work in a high level area where installed those different guardrails.

3.1.2. The 2-D pictures of guardrail with true-scaled worker picture printed on the paper

The second feeling measurement tool (Type II) is 2-D pictures of different guardrail types, compared with the workers' dimension that printed on the hardcopy paper. For this tool, the picture of true-scaled guardrail is inserted to the picture of true-scaled worker and construction site environment as shown in Fig. 2. It illustrates a worker who works in a high level area that installed the fall protection system by using different types of the guardrails. Those pictures were used to measure workers' feelings when they were selected to look at the pictures and to respond their feelings in term of safety and convenience.

3.1.3. Virtual Reality (VR) models illustrated in Virtual Environment (VE) tool

Spelz [13] described that Virtual Reality (VR) technology is an information technology that can be used to enhance users' imagination because of its advantages, such as 3-D model presentation, model movement, animation, sound, model responding, and virtual environment. In design stage, Virtual Reality models can be applied to enhance communication capability [14]. Costello [15] classified Virtual Reality technology into 3 systems, including non-immersive (desktop) system, semi-immersive protection system, and full immersive head-mounted display system. Kalawsky [16] summarized that Virtual Reality (VR) is emerging as a very powerful educational tool that has the potential to provide the higher education establishment with a powerful and effective educational environment. The qualitative performance of VR systems is depended on 6 main features, consisting of resolution, perception, navigation skills, field of regard, lag, and sense of immersion.

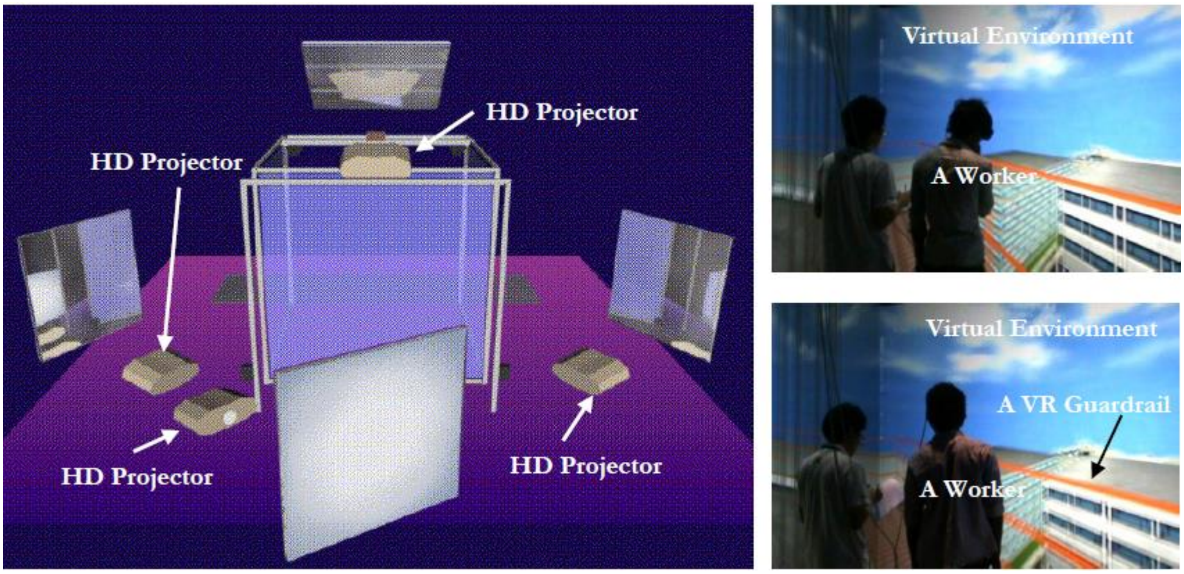
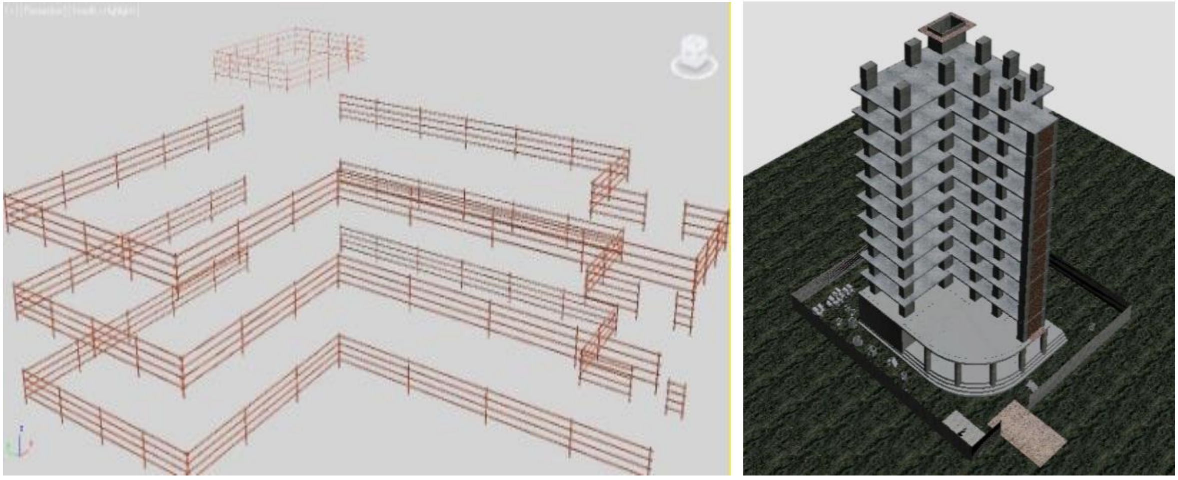


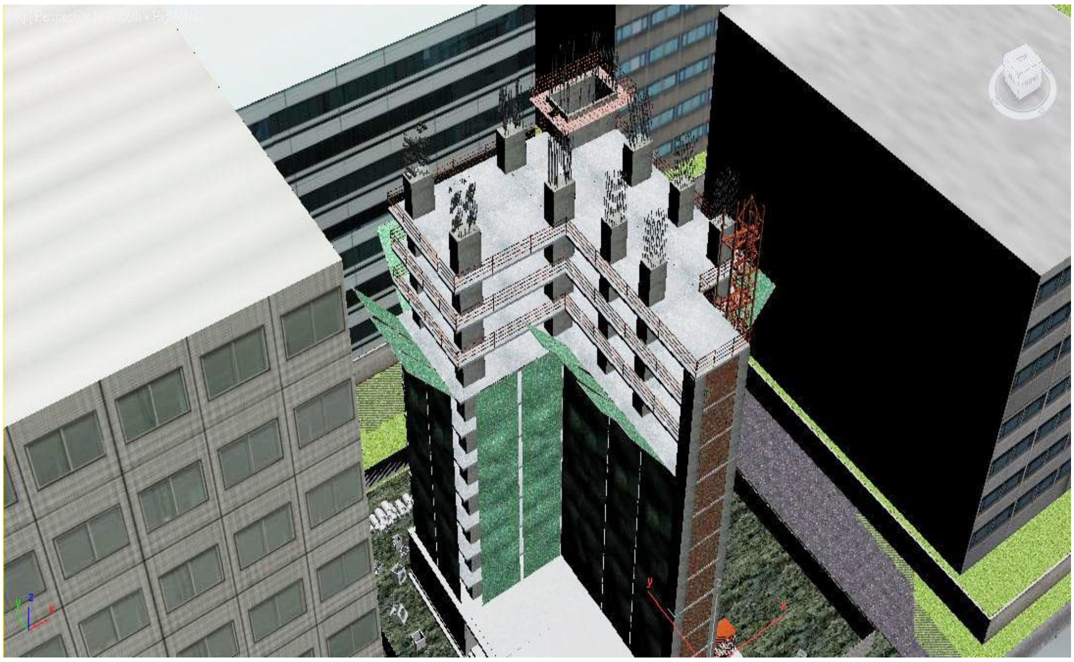
Fig.3. The Cave Automatic Virtual Environment (CAVE) (modified from [17]).

For enhancing the reality of construction site environment, the Cave Automatic Virtual Environment (CAVE) as shown in Fig. 3 was applied to develop a workers' feeling measurement tool (Type III). It is one kind of full immersive Virtual Reality (VR) system which has high realistic illustration. The CAVE consists of four sides of the screen which projected figures by four High Definition (HD) projectors. The projectors were controlled by five personal computers (PC): 1st to 4th PC which control 1st to 4th projector, and 5th PC is used to control movement of models in virtual environment by receiving input data from movement control equipment called "Wanda" (mouse and pointer). The users have to use special (3-D) glasses in CAVE for looking at the virtual reality models, and control movement of models as well as walk through by using Wanda [18] as shown in Fig. 3.

True-scaled VR models of a high-rise building, different types of guardrail, and environment of construction site were created by the animation software. The VR models of different guardrail types as shown in Fig. 4(a) were installed in a VR model of the high-rise building construction project as shown in Fig. 4(b) which illustrated in the virtual environment as shown in Fig. 4(c). Those models were simulated and run by the programming in the CAVE as shown in Fig. 5. It was used to be a feeling measurement tool (Type III) for workers in order to rate their feeling levels (safety and convenience feeling levels) when they were selected to walk through the virtual reality models in the CAVE.



(a) VR models of guardrail (b) A VR model of the high-rise building



(c) Virtual environment

Fig. 4. The VR models of guardrail in a high-rise building construction project and virtual environment.

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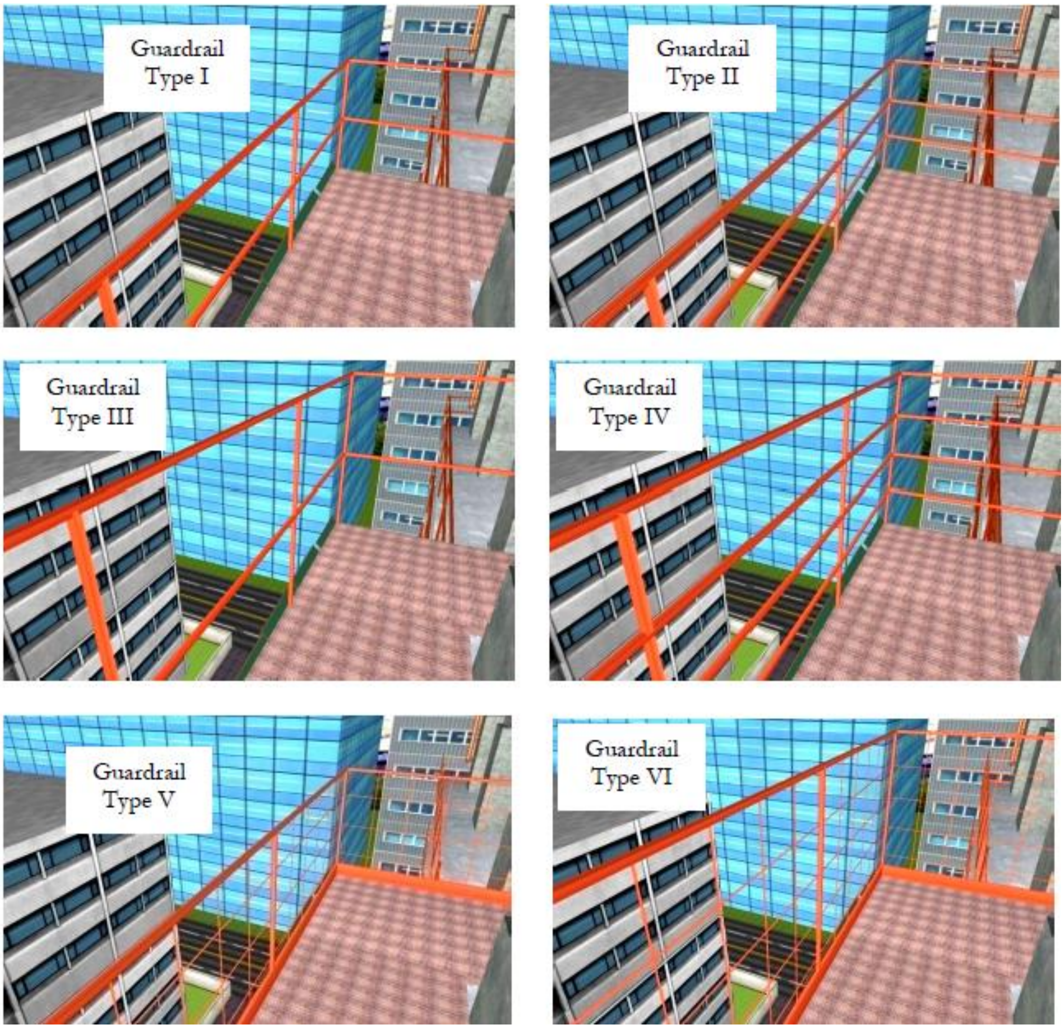


Fig. 5. VR models of different guardrail types in a VR model of a high-rise building simulated in the CAVE.

3.2. Methodologies for Experimenting the Efficiency of Feeling Measurement Tools

In this research, the efficiency of feeling measurement tool was investigated by the variation of workers' feeling responding. The workers were tested on both of their safety and convenience feelings by using each tool based on the assumption that if the variation of workers' feeling responding by a feeling measurement tool is lower than the others, the efficiency of that feeling measurement tool will be higher than the others. The methods for construction workers to respond their feelings that were used to verify the efficiency of the feeing measurement tools can be described as follows:

3.2.1. Questionnaire development for rating workers' feelings

The questionnaires were developed for the workers, which were used to respond their feelings when they were tested by the tools. The important questions in the questionnaire are the rating scale of feelings, such as safety and convenience feelings with 5 levels (5 = very high, 4 = high, 3 = medium, 2 = low, and 1 = very low). The workers will respond their levels of safety and convenience feelings from 1 to 5 scaling as though they work in the real construction project that installed each type of the guardrail for fall protection. The six types of the guardrail were selected for testing workers' feelings. An example of a construction worker's feeling levels rated for each type of the guardrail can be presented in Table 1.

Table 1. An example of feeling levels of a construction worker rated for each type of the guardrail.

Guardrail Types	**Safety feeling level (1-5)** Testing				**Convenience feeling level (1-5)** Testing			
	No. 1	No. 2	No. 3	No. 4	No. 1	No. 2	No. 3	No. 4
Type I	2	3	2	1	1	2	1	1
Type II	4	3	3	4	4	2	2	3
Type III	3	3	3	3	2	3	2	3
Type IV	4	4	4	4	3	4	4	4
Type V	5	4	4	3	4	3	3	3
Type VI	5	5	5	5	5	5	5	5

3.2.2. Data collection

The 10 construction workers who had experiences in high-rise building construction projects were randomly selected to be the respondents. For decreasing of bias occurrence because of their remembrances, they were tested their safety and convenience feelings by using the 3 types of feeling measurement tools in 4 testing (Testing No.1 – Testing No.4) per one type of the guardrail. For each testing, the feeling measurement tools were changed the rank (1-3) as shown in Table 2. The 3 types of the tool were verified their efficiency of feeling measurement. Figure 6 shows 2 types of feeling measurement tools, such as 2-D pictures of guardrail printed on the paper (Type I) and 2-D pictures of guardrail with the true-scaled worker picture printed on the paper (Type II) that were verified by a construction worker. Moreover, Figure 7 shows feeling measurement tool Type III (VR models of guardrail that run in CAVE) were verified its efficiency by 10 workers. Those workers were built their feelings by walking through the VR high-rise building model in CAVE by starting their walking from the ground floor. Then, they were simulated to go upstairs by using a construction elevator to the 20th floor level that installed the different types of the guardrail as shown in Fig. 7(a). After that, they rated their levels of safety and convenience feelings for different types of the guardrail as shown in Fig. 7(b) and Fig. 7(c), respectively.

Table 2. Different ranks of feeling measurement tools used for one worker to rate feeling levels.

Testing No.	**Ranks of tools** Type I	Type II	Type III
1	1	2	3
2	2	1	3
3	2	3	1
4	3	2	1

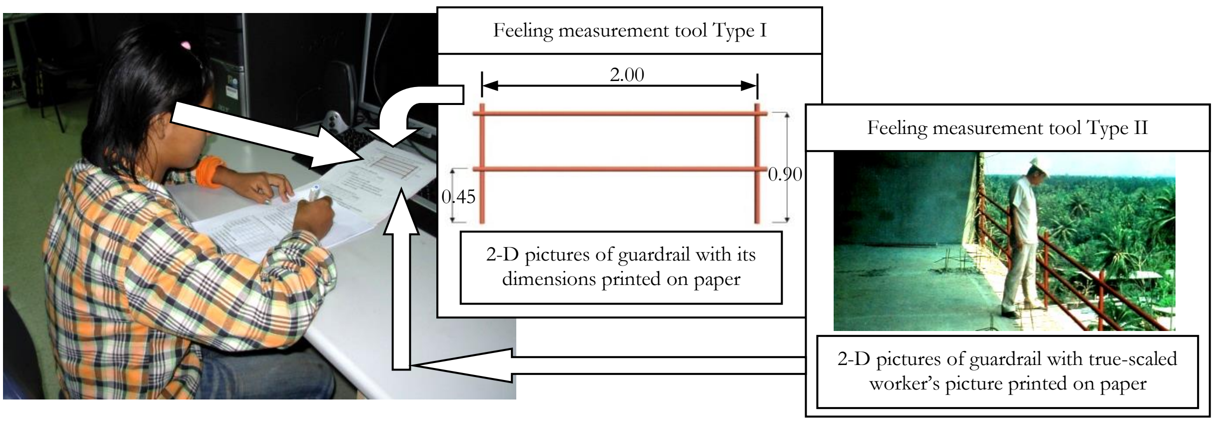


Fig. 6. Rating of feeling levels of a worker by using feeling measurement tool Type I and Type II.

(a) The workers were built their feelings by walking through the VR model in the CAVE.

(b) Rating of workers' feeling levels for guardrail Type I and II by feeling measurement tool Type III.

(c) Rating of workers' feeling levels for guardrail Type III and VI by feeling measurement tool Type III.

Fig. 7. Rating of workers' feeling levels for different guardrail types by feeling measurement tool Type III.

3.2.3. Data analysis

The rating scales (1-5) or levels of 10 construction workers' feelings on both safety and convenience for different types of the guardrail that were measured by 3 types of the feeling measurement tool were analyzed to obtain the Mean ($\bar{X}$) and Standard Deviation (**$S.D.$**) of feeling level by using Eq. (1) and Eq. (2). Then, the Coefficient of Variation (**$C.V.$**) can be determined as presented in Eq. (3) [19].

$$\bar{X} = \frac{\sum x}{N} \tag{1}$$

$$S.D. = \sqrt{\frac{N\sum x^2 - (\sum x)^2}{N(N-1)}} \tag{2}$$

$$C.V. = \frac{S.D.}{\bar{X}} \tag{3}$$

where x = Level of construction workers' feeling (1-5);
N = Number of testing (N = 4; Testing No.1 - Testing No.4).

The $S.D.$ and $C.V.$ can be used to indicate the variation of data. However, the Coefficient of Variation ($C.V.$) is better indicator to indicate the variation, when considering more than 2 data sets and the Mean ($\bar{X}$) of data are more different [19]. In this research, the 6 data sets with different mean value were used. Thus, the $C.V.$ was only used to indicate the variation of workers' feelings when they rated their feeling levels by using each type of the feeling measurement tool for different types of the guardrail. If the $C.V.$ of workers' feeling levels measured by a feeling measurement tool are lower than those measured by the others, it will be indicated that the variation of workers' feelings measured by that tool is lower than measured by the others, and also indicated that the efficiency of that feeling measurement tool is higher than efficiency of the others. The examples of $C.V.$ of a worker's safety feeling that was measured by a feeling measurement tool in 4 times of testing are presented in Table 3.

Table 3. Examples of $C.V.$ of a worker's safety feeling measured by a feeling measurement tool.

Guardrail Types	**Safety feeling levels** (1-5) Testing				$\bar{X}$	$S.D.$	$C.V.$
	No. 1	No. 2	No. 3	No. 4			
Type I	2	3	2	1	2.00	0.82	0.41
Type II	4	3	3	4	3.50	0.58	0.16
Type III	3	3	3	3	3.00	0.00	0.00
Type IV	4	4	4	4	4.00	0.00	0.00
Type V	5	4	4	3	4.00	0.82	0.20
Type VI	5	5	5	5	5.00	0.00	0.00

The all $C.V.$ of a worker's feelings rated for six types of guardrail that measured by feeling measurement tools (Type I, Type II, and Type III) were analyzed to obtain the representative of those $C.V.$ value by using the $Median$ of them, respectively. The $Median$ is the middle value of a sorted list of data set (from minimum to maximum value). It is commonly used to measure the property of data set. The advantage of the $Median$ when compared with the Mean or Average value is the $Median$ is not skewed so much by extremely small or large value. Thus, it is a better idea for finding the representative or typical value of data set when the data in the data set is skewed so much [20]. The middle number of a data set can be found by using Eq. (4). $Median$ value of data set is value of middle number (for an odd number of values) or average of two middle numbers (for an event number of values).

$$Middle\ number = \frac{n+1}{2} \tag{4}$$

where, n = Number of data in a data set.

Then, $Median$ of $C.V.$ of 10 workers' feelings measured by the feeling measurement tools (Type I, Type II, and Type III) were analyzed again to obtain the representative $Median$ for all workers, respectively.

3.3. Results of the Experiment of Feeling Measurement Tools Efficiency

The efficiency of feeilng measurement tools were experimented by considering the $Median$ of $C.V.$ of all workers' feelings. Table 4 presents the $Median$ of $C.V.$ of a worker's feelings (safety and convenience feelings) that measured by a feeling measurement tool.

Table 4. The *Median* of *C.V.* of a worker's feelings measured by a feeling measurement tool.

Guardrail Types	Safety feeling			Convenience feeling		
	$\bar{X}$	*S.D.*	*C.V.*	$\bar{X}$	*S.D.*	*C.V.*
Type I	2.00	0.82	0.41	1.25	0.50	0.40
Type II	3.50	0.58	0.16	2.75	0.96	0.35
Type III	3.00	0.00	0.00	2.50	0.58	0.23
Type IV	4.00	0.00	0.00	3.75	0.50	0.13
Type V	4.00	0.82	0.20	3.25	0.50	0.15
Type VI	5.00	0.00	0.00	5.00	0.00	0.00
Median	-	-	0.08	-	-	0.19

The *Median* of *C.V.* of all workers' feelings that were measured by Tool Type I, Type II, and Type III are illustrated in Table 5, Table 6, and Table 7, respectively. The workers' feelings were analyzed to obtain the representative (*Median*) of the variation of safety feeling, convenience feeling, and both safety and convenience feelings.

Table 5. The *Median* of *C.V.* of all workers' feelings measured by Tool Type I.

Worker No.	Safety Feeling *Median* of *C.V.*	Convenience Feeling *Median* of *C.V.*	Safety & Convenience feelings *Median* of *C.V.*
Worker No. 1	0.08	0.19	
Worker No. 2	0.43	0.46	
Worker No. 3	0.13	0.28	
Worker No. 4	0.40	0.40	
Worker No. 5	0.14	0.13	
Worker No. 6	0.26	0.22	
Worker No. 7	0.28	0.20	
Worker No. 8	0.25	0.16	
Worker No. 9	0.25	0.27	
Worker No. 10	0.14	0.21	
Median (all workers)	**0.25**	**0.22**	**0.24**

Table 6. The *Median* of *C.V.* of all workers' feelings measured by Tool Type II.

Worker No.	Safety Feeling *Median* of *C.V.*	Convenience Feeling *Median* of *C.V.*	Safety & Convenience feelings *Median* of *C.V.*
Worker No. 1	0.08	0.25	
Worker No. 2	0.32	0.31	
Worker No. 3	0.08	0.26	
Worker No. 4	0.31	0.31	
Worker No. 5	0.14	0.14	
Worker No. 6	0.32	0.23	
Worker No. 7	0.31	0.15	
Worker No. 8	0.21	0.16	
Worker No. 9	0.26	0.25	
Worker No. 10	0.38	0.21	
Median (all workers)	**0.29**	**0.24**	**0.25**

Table 7. The *Median* of *C.V.* of all workers' feelings measured by Tool Type III.

Worker No.	Safety Feeling *Median* of *C.V.*	Convenience Feeling *Median* of *C.V.*	Safety & Convenience feelings *Median* of *C.V.*
Worker No. 1	0.06	0.15	
Worker No. 2	0.25	0.25	
Worker No. 3	0.06	0.28	
Worker No. 4	0.18	0.29	
Worker No. 5	0.14	0.00	
Worker No. 6	0.18	0.23	
Worker No. 7	0.16	0.20	
Worker No. 8	0.19	0.20	
Worker No. 9	0.29	0.18	
Worker No. 10	0.38	0.19	
Median (all workers)	**0.18**	**0.20**	**0.19**

Table 8 presents the representative (*Median*) of variation (*C.V.*) of all workers' feelings measured by the three types of the feeling measurement tool. The results show that the *Median* of *C.V.* of all workers' feelings, such as safety, convenience, and both safety and convenience feelings that were measured by the measurement tool Type III are lower than measured by the measurement tools Type I and Type II so that the variation of workers' feelings that were measured by measurement tool Type III is lower than measured by the measurement tools Type I and Type II. From the results, it can be summarized that the performance of the feeling measurement tool Type III is higher than the feeling measurement tools Type I and Type II.

Table 8. The *Median* of *C.V.* of all workers' feelings measured by 3 types of the measurement tool.

Feeling measurement tools	Safety Feeling *Median* of *C.V.*	Convenience Feeling *Median* of *C.V.*	Safety & Convenience Feeling *Median* of *C.V.*
Tool Type I	0.25	0.22	0.24
Tool Type II	0.29	0.24	0.25
Tool Type III	0.18	0.20	0.19

4. A Case Study of Guardrail Design by Considering Cost and Construction Workers' Feelings

4.1. Methodologies

4.1.1. Design of alternative guardrails

Six types of the guardrail as shown in Fig. 1 were used to protect construction workers from falling from height in a high-rise building construction project. They were designed and used to be alternative guardrail types in this case study. Some types of them would be selected under considered factors to obtain a suitable type of the guardrail.

4.1.2. Considered factors

Yoon and Hwang [21] proposed decision making under multiple attributes for quantitative data. In this case study, the multiple considered factors are the factors that used to consider the suitable type of guardrail. Three factors, such as cost, workers' safety feeling, and workers' convenience feeling were the factors that were used for considering the suitable guardrail type. The cost of each guardrail type was estimated by the experts (designers), based on material cost and labor cost of assambly and installation.

Moreover, the levels of workers' feelings, such as safety and convenience feelings were rated by 10 construction workers who had experiences in high-rise building construction projects. They rated their feeling levels by using a feeling measurement tool. In this case study, it is virtual reality models in a vertual environment or CAVE (Tool Type III). Due to the above results, its efficiency is higher than the other feeling measurement tools.

4.1.3. Determine weigh of the factors

In this research, the level of importance or weigh of each factor that was used to consider the suitable type of the guardrail are deferent. Weigh of factors were compared by perceptions of 6 experts (designers) who had high experience in guardrail design. They compared level of importance of factors by pair-wise comparision, and were analyzed by using Analytic Hierarchy Process (AHP) method that was stated by Saaty [22]. The level of importance consists of 5 scales for pair-wise comparison, such as (1) equal importance, (3) weak importance, (5) strong importance, (7) very strong importance and (9) absolute importance. The levels of importance or weigh of each factor (W_f) rated by an expert are the average weight which was analyzed by pair-wise comparison matrix for n factors.

However, the consistency of the result should be proven by Consistency Ratio ($C.R.$) which is calculated by Consistency Index ($C.I.$) and Random Index ($R.I.$) as shown in Eq. (5), Eq. (6), and Eq. (7). The $C.R.$ can be used to ensure the consistent of respondents' perceptions. The λ_{max} equals to summation of consistency vector divided by n (numbers of factor). In this case, n is equal to 3.

$$C.I. = \frac{\lambda_{\max} - n}{n - 1} \tag{5}$$

$$R.I. = 1.56 \text{ (for } n = 3\text{) [22]} \tag{6}$$

$$C.R. = \frac{C.I.}{R.I.} \tag{7}$$

If Consistency Ratio ($C.R.$) is lower than 0.1, the result will be accepted; on the other hand, if $C.R.$ is greater than 0.1, the result will not be accepted [22].

Then, the representative weight of each factor from all experts is determined. It is average weight of factor from all experts ($\overline{W}$) that can be determined by Eq. (8).

$$\overline{W} = \frac{\sum W_f}{N} \tag{8}$$

where N = Number of experts (In this case, N = 6).

4.1.4. Selecting the suitable type of the guardrails

For selecting the suitable type of guardrail, the alternative guardrails were compared under the considered factors which had different average weight ($\overline{W}$). In this case, the 6 types of the guardrail were compared under considered factors, such as cost of guardrails and 10 construction workers' feelings and analyzed by the AHP method to obtain the levels of importance of each guardrail type ($L.I._g$) under each considered factors. Then, the level of importance of each guardrail that is multiplied by the average weight ($\overline{W}$) of considered factors will be determined to be the weighted level of importance ($L.I._w$) of the guardrail as shown in Eq. (9). Finally, summation of $L.I._w$ of all considered factors is the level of total importance ($L.I._{total}$) of each guardrail type as shown in Eq. (10).

$$L.I._w = \overline{W} \times L.I._g \tag{9}$$

$$L.I._{total} = \sum L.I._w \tag{10}$$

4.2. Results of Guardrail Design by Considering Cost and Construction Workers' Feelings

4.2.1. The average weight of factors from all experts ($\overline{W}$)

The average weight of factors from all experts ($\overline{W}$) that was used to select the suitable guardrail type are presented in Table 9. It shows that the average weight of the safety feeling is higher than the average weight of convenience feeling and the cost, respectively. From this analysis, it can be concluded that the consistency of the results is high because the Consistency Ratio (*C.R.*) is very low (*C.R.* = 0.0).

Table 9. The average weight of the considered factors from all experts, used for guardrail design.

Considered Factors	**Weight of factors (W_f)**						**Average weight ($\overline{W}$)**
	Expert No.1	Expert No.2	Expert No.3	Expert No.4	Expert No.5	Expert No.6	
Cost	0.09	0.46	0.14	0.13	0.11	0.11	**0.174**
Safety feeling	0.78	0.46	0.72	0.22	0.74	0.80	**0.620**
Convenience feeling	0.13	0.08	0.14	0.65	0.15	0.09	**0.207**

4.2.2. Level of importance of each guardrail type ($L.I._g$)

From pair-wise comparison of cost of guardrail by 6 experts and workers' feeling by 10 construction workers for the 6 types of guardrail and analysis by the AHP method, the levels of importance of each guardrail type ($L.I._g$) can be presented in Table 10. It shows that for each considered factors, the levels of importance of each guardrail type are different.

Table 10. Levels of importance of each guardrail type ($L.I._g$) classified by the considered factors.

Guardrail Types	***I.L.$_g$***		
	Cost*	Safety feeling**	Convenience feeling**
Type I	0.191	0.144	0.133
Type II	0.179	0.123	0.142
Type III	0.138	0.178	0.161
Type IV	0.104	0.183	0.195
Type V	0.206	0.188	0.179
Type VI	0.183	0.184	0.191

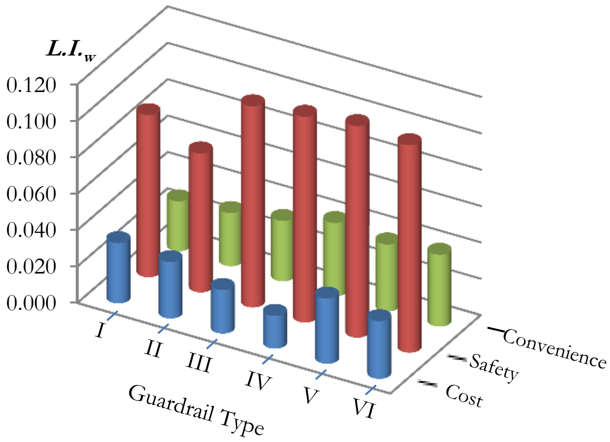
Remarks: * compared by 6 experts, ** compared by 10 workers

4.2.3. Level of the total importance of guardrails ($L.I.total$)

From summation of the weighted level of importance for each guardrail type, it can be obtained the total level of importance of the guardrails as shown in Table 11 and Fig. 8. They present that the guardrail type V has the highest level of the total importance ($L.I._{total}$ = 0.189) that is closed to the guardrail type VI ($L.I._{total}$ = 0.185). The $L.I._{total}$ of guardrail Type IV, Type III, Type I, and Type II are lower than Type V and Type VI, respectively.

Table 11. Level of the total importance of guardrails ($L.I._{total}$) for selecting suitable types of guardrail.

Guardrail Types	Weighted level of importance of guardrails ($L.I._w$)			Level of total importance ($L.I._{total}$)
	Cost ($\overline{W}$ = 0.174)	Safety feeling ($\overline{W}$ = 0.620)	Convenience feeling ($\overline{W}$ = 0.207)	
Type I	0.174 x 0.191	0.620 x 0.144	0.207 x 0.133	0.150
Type II	0.174 x 0.179	0.620 x 0.123	0.207 x 0.142	0.137
Type III	0.174 x 0.138	0.620 x 0.178	0.207 x 0.161	0.168
Type IV	0.174 x 0.104	0.620 x 0.183	0.207 x 0.195	0.171
Type V	0.174 x 0.206	0.620 x 0.188	0.207 x 0.179	**0.189**
Type VI	0.174 x 0.183	0.620 x 0.184	0.207 x 0.191	0.185



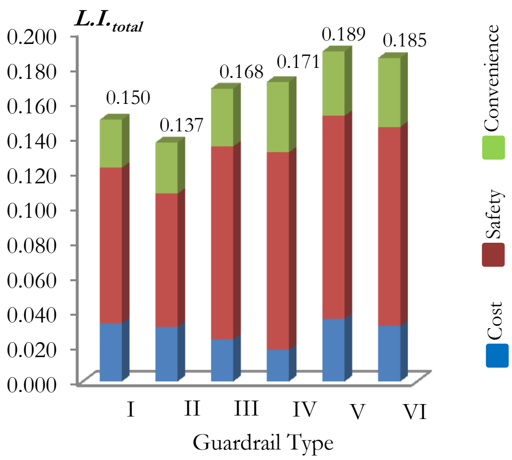
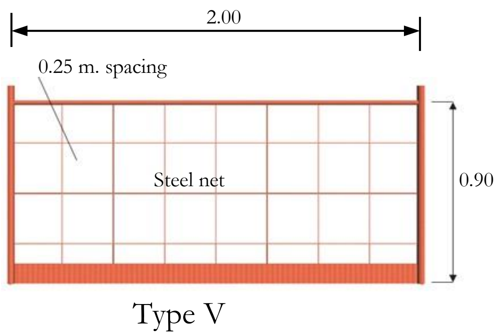


Fig. 8. Level of the total importance ($L.I._{total}$) of each guardrail type.

4.2.4. Results of selecting the suitable types of the guardrail

From level of the total importance (L.I.total) of each guardrail type, the L.I.total of guardrail Type V and Type VI are the highest total importance. Therefore, the suitable guardrail types are guardrail Type V and Type VI as shown in Fig. 9.



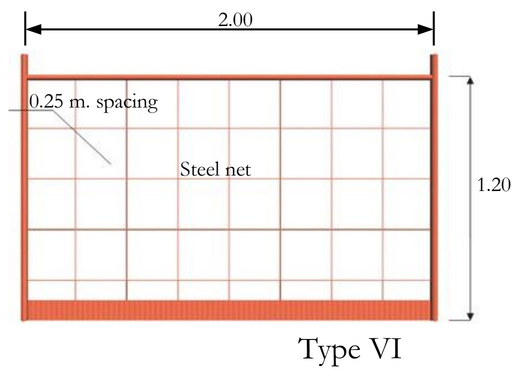


Fig. 9. The suitable guardrails designed by considering the cost factor and workers' feeling factors.

5. Conclusions

The objectives of this research are to verify the performance of workers' feeling measurement tools and propose a case study of the safety guardrails design by considering workers' feelings in a high-rise building construction project. The performance of three types of feeling measurement tool was verified by the variation (C.V.) of construction workers' feelings, such as safety feeling and convenience feeling. In the case study, the most effective feeling measurement tool was selected and used to design the safety guardrail by considering three factors, including cost of guardrail, safety feeling, and convenience feeling of construction workers. The cost of guardrail was estimated and compared by six experts (designers) and the workers' feelings were rated and compared by ten construction workers who had experiences in high-rise building construction projects. The six types of safety guardrail were designed and compared by pair-wise comparison. The AHP method was used to analyze the weight of factors and select the suitable type of guardrail.

From the performance comparison among the three types of workers' feeling measurement tool, it can be concluded that the VR models run in Virtual Environment (VE) equipment called "CAVE", is the highest performance tools that can be used to measure construction workers' feelings. It can be used to measure the workers' feelings for design the suitable type of the guardrail. In the case study of the experimental of guardrail design for a high-rise building construction project by considering cost and the workers' feelings, the result shows that we can design the suitable type of the guardrail by considering not only the cost factor but also the workers' feeling factors.

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