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Opportunity Efficiency - Use Uncertainty Analysis to Evaluate Risks in Construction

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Abstract

In central Taiwan, around the Taichung basin, the ground condition is boulders with red soils and high ground water level. Local technicians have developed an unusual soil excavation method to build the so-called "soil retaining columns". It is cheap, practical and highly efficient. However it is fraught with risk and uncertainty.

In general, use of the injury severity method in occupational injury evaluation is a good solution. But, the method seems unsuitable for high risk situation in construction sites. Traditionally, there are 3 excavation methods to frame the soil retaining piles. Their risk distributions are not similar. Thus, we can't use the same safety investment budget when we choose different excavation method. In this study, for increase the exactness of "risk quantity", we focus on the different "risk distribution". Based our risk evaluation of the "hazard uncertainty" concept and introducing the notion of "opportunity efficiency" to modify usage of the "risk severity" analysis; this concept will increase the accuracy of safety investment evaluations.

Keywords: Opportunity efficiency, Risk evaluate, Occupational safety, Soil retaining columns

1. Introduction

When comparing the occupational injury risks of different excavation methods, the problem is how to quantify the different degrees of occupational injuries. In recent years, "injury severity" has emerged as a mature method for safety investment-benefit analysis. This assessment method focuses on occupational injury damage. However, discussion about disproportionate risks in construction sites is not enough. Traditionally the risk distribution is hard to define. There are 3 excavation methods to frame the soil retaining piles. But their risk distributions are dissimilar. During the study, we develop one notion "hazard uncertainty" as the fundamental consideration in injury assessment. We evaluate the "Uncertainty" distribution by an Uncertainty Index (U.I.). Furthermore, for more accurate risk estimation, we provide an "Opportunity Efficiency" (O.E.) index. In this paper, we frame 4 quantification steps: (1) Hazard analysis (2) Hazard severity evaluation (3) Hazard uncertainty distribution and (4) Opportunity efficiency analysis. By those steps, many different construction methods can be defined their "risk quantification" exactly.

2. The Introduction of "Soil Retaining Columns"

The ground condition of Taichung basin is boulders mixed with red soil and high ground water level. Local technicians have developed an unusual soil excavation method to build the so-called "soil retaining columns" (Figure 1). The excavation method is very flexible. It can be combined with two or more excavation methods to finish one work by different ground conditions. It is cheap, practical and highly efficient but fraught with uncertainty and risk. Thus, some hazards exist on site. We take a local excavation method as an example below (H.C.Hsu, 2003);

<Figure 1>

In Taiwan, there are 3 methods for build the “soil retaining columns”. They are

Manual excavation after lowering groundwater level

Mechanical excavation

Manual diving excavation

Most of digging labors choose the (1) manual excavation after lowering groundwater level method for excavation because it is the most safety way. But, when we cannot draw down the groundwater level, excavation must be taken under the groundwater level. Then we choose the (3) manual diving excavation method. The engineer might choose the (2) mechanical excavation method if the situation permits (e.g. the soil self-supporting condition can not be exceeded over 5m).

We take the (3) manual diving excavation method for our research tropic.

In general, method (3) contains 9 steps as follows (Institute of Occupational Safety & Health, 1997):

Step1: Site survey and construction preparation.

Step2: Set up working canopy (triangle camp) (Figure 2).

Step3: Excavate guide pit (1.5m depth), place soil trash pit, and set up the concrete form work (Figure 3).

Step4: Mix red soil & cement with a 4:1 ratio to make fill balls. These balls will fill in the spaces between gravel and boulder to prevent collapsing of pit (Figure 4 & Figure 5).

Step5: The diver enters the guide pit for diving excavation (Figure 6). For safety, a diver must wear many pieces of equipment (Figure 7) such as diving suit, hot water circulation pump to maintain body temperature, a diving bell for air circulation (Figure 8) and a microphone for communication, etc. Hazards always caused by equipment breakdown.

<Figure 2 and 3>

Step6: Excavate down and send out trash soil by well bucket (Figure 9).

Step7: Pass down the filling balls to fill in the spaces between the gaps of stone.

Step8: Having reached the desired depth, pass down the steel bar cage for reinforcement.

Step9: Pour the concrete.

<Figure 4-9>

Top view and section placed are shown in Figure 10 & Figure 11.

<Figure10-11>

3. The Operating Items in Hazard Analysis

In the 1st step of 4 quantification steps, we use 3 processes to analyze those possible hazards in different construction methods as follow:

In the process A, we can list 9 working steps of the “soil retaining column”.

In the process B, we can decide the 10 working tasks by analyze these 9 steps as shown in Table 1 (Institute of Occupational Safety & Health, 1997).

<Table 1>

In general, operating hazards are due to unsafe behaviors & situations. The two analysis tropics can help us understanding the possible hazards in process C as shown in Table 2.

<Table 2>

When we understand the possible hazard types by each working tasks, we can decide the hazards influence in this excavation method. During the study, the data cannot show “What’s working method by each hazard?” in original information. But we choose the most possible hazard types in actual construction site, and abandon less important hazard. Therefore, we collect 5 possible hazards list in Table 3.

<Table 3>

4. The Analysis of Hazard Severity

Table 4 lists the numbers of persons injured from 1987 to 1996. It is divided by hazard types (Institute of Occupational Safety & Health, 1997). During the study, we choose 5 the most possible hazard types for assessment. The normal injury level assessment method contains the lost working days method, judge theorem method, value analysis method and economic loss method (J.X.Zhou, 2006). We combine the economic loss method and lost working days method, and use "the hazard severity γ"as the foundation of the injury severity evaluation.

(1) Cripple severity coefficient $\alpha = \frac{\text{Cripple Insurance Indemnification Money}}{\text{Dead Insurance Indemnification Money}}$

(2) Hurt severity coefficient $\beta = \frac{\text{Hurt Insurance Indemnification Money}}{\text{Dead Insurance Indemnification Money}}$

(3) Hazard severity coefficient $\gamma = \frac{n_1 + \alpha n_2 + \beta n_3}{N}$ Eq.(4.1)

In the equation, N means the total number of occupational injuries, n_1 means the number of dead persons; n_2 means the number of crippled persons; n_3 means the number of hurt persons.

The mode we defined the α and β value by "the insurance indemnifications money" can modified the "man power value" question by "lost working days".

We collect the number of insurance indemnifications P_T between 1987~1996 by construction injury, and the insurance indemnification money P_M between 1987~1996, these statistics are shown in Table 4.

<Table 4>

We can calculate the cripple severity coefficient α and hurt severity coefficient β by Table 4. Thus, by economic loss method, we can get the hazard severity coefficient γ for different hazard type to list them in Table 5. Let's take the "falling down" for example:

$$\alpha = \frac{248}{328} = 0.756 \qquad \beta = \frac{8.5}{328} = 0.026$$

$$\gamma = \frac{665 + 243\alpha + 9936\beta}{10{,}844.} = 0.102$$

We calculate the hazard relative severity coefficient γ'; it can be provided the same comparative foundation (X.Li, 2005). We take the minimize hazard severity coefficient γ to be equal to 1.0. Again take the "falling down" for example:

$$\gamma' = \frac{\gamma_2}{\gamma_1} = \frac{0.102}{0.056} = 1.817$$

<Table 5>

We can get the severity sequence in the 5 hazard types as follow;

Electric shock > Toppling over > Falling down > Objects crashing > Rolling in, Clipping in

5. The Occupational Injury Grade

In general public occupational injury statistics are divided in 3 grades "cripple, hurt, dead". But this division cannot be responded to risk quality work exactly. During the study, the occupational injury severities are divided into 7 grades (Health and Safety Commission, 1995). We list them as Table 6.

<Table 6>

6. Uncertainty Distributions

To consider the risk distributions efficiently, we take the root-mean-square deviation ±1σ to be the range about the hazard distribution statistics by the Table 5.1. The normality distribution will contain 68% hazard distribution. The reason we abandon the other ±16% is because those occupational insurance statistical data didn't record the causes of the injuries (R.Flanagan, G.Norman, 1993), (C. Fefferman, 1979). We define the various hazard level average values I_μ by different working methods, shown as Eq. (6.1)

$$I_{\mu} = \frac{1}{N}\sum_{i=1}^{N}\chi_{i} \qquad \text{Eq. (6.1)}$$

χ_{i} ; $i = 1 \sim N$ The hazard level

And we use Eq. (6.2) to calculate the root-mean-square deviation σ

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\chi_{i} - I_{\mu})^{2}} \qquad \text{Eq (6.2)}$$

Thus, we take the ±1σ range I_p and I_o for the pessimistic and optimistic possible injury level when n=1, as shown in Eq. (6.3)

$$I_{p} = I_{\mu} + n\sigma$$

$$I_{0} = I_{\mu} - n\sigma \qquad \text{Eq. (6.3)}$$

The hazard uncertainty distribution diagram is shown in Figure 12.
<Figure 12>

Therefore, we define an uncertainty distribution index Δ as Eq. (6.4.)

Uncertainty distribution index

$$\Delta = \frac{I_{p} - I_{o}}{2} = \frac{1}{2}[(I_{\mu} + n\sigma) - (I_{\mu} - n\sigma)] = n\sigma \qquad \text{Eq. (6.4)}$$

During the study, we take n=1.0 for define an uncertainty index U.I. for different hazard ranges.

Then take the index to be equal to 1.0 when that item 『hazard severity γ』 is at its lowest value. We can get another relative index as Eq. (6.5)

Uncertainty index

$$U.I. = \frac{\Delta_{i}}{\Delta_{0}} \quad i = 1 \sim n \qquad \text{Eq. (6.5)}$$

Δ_0 means the lowest possible value for the 『hazard severity γ』

Because the existing data focus on “Injury type” merely, it does not show “the reason of injuries”. By that information, all injury types of various construction methods cannot be divided. Let’s take the “falling down” for example. Suppose the “hurt” grade is equal to average 2.0, the “cripple” grade is equal to average 5.0, the “dead” grade is equal to 7.0. We can know I_{μ}=2.5, σ=1.2 by basic statistic analysis. It is not rational that use the same I_{μ} & σ in different construction method. So we modify their I_{μ} & σ by different construction method. For example, the “falling down in manual excavation after lowering groundwater level”, we choose the I_{μ}=3.0, σ=1.0, thus,

$$I_{p} = 3 + 1 = 4 \qquad I_{O} = 3 - 1 = 2 \qquad \Delta = \frac{4-2}{2} = 1$$

Uncertainty distribution index $U.I. = \frac{\Delta_1}{\Delta_0} = \frac{1}{1.5} = 0.667$

When the U.I. is large, it means the hazard uncertainty is big. The results are listed in Table 7.
<Table 7>

7. The Analysis of Opportunistic Effect

We have the hazard severity (γ) by Eq. (4.1). Using "safety investment economic analysis", we define the Hazard Index (H.I.) as Eq. (7.1.)

Hazard Index (H.I.) = (γ')*(U.I.) Eq. (7.1)

Let's take the "falling down in manual excavation after lowering groundwater level" for example:

(H.I.) = $1.817 \times 0.667 = 1.212$

This index provides an objective reference meaning. The risk level follows when the UI value is known. Starting from the insurance indemnification money P_M in Table 4.1, we can calculate the insurance indemnification money ratio for different hazard types P_r. The index shows the real hazard cost. The P_r (Insurance Indemnification Ratio) is defined as follows:

$$P_r = \frac{P_m}{\sum_{i=1}^{n} P_{mi}}$$ $i=1\sim n$; n means the numbers of this construction possible hazards. Eq. (7.2)

Let's take the "falling down in manual excavation after lowering groundwater level" for example:

$$P_r = \frac{362,840.}{813,236.} = 0.446$$

We can understand the relationship between cost & risk by the cost index P_r. Following the necessity of "opportunity quantity", we provide an index, the Opportunity Efficiency (O.E.) shown as Eq. (7.3). Opportunity efficiency is the efficiency occupational injury budgets. The result is shown in Table 8.

Opportunity Efficiency (O.E.) = $(H.I.)/P_r$ (Eq.7.3)
<Table 8>

$$(O.E.) = \frac{1.212}{0.446} = 2.716$$

By this efficiency assessment, we can evaluate the opportunity efficiencies of different construction methods & different working items. The results prove that the OE method shows real necessity when compared with the injury severity method.

8. Conclusions

How much money must be budgeted for safety?

Which possibilities are so improbable that they should not be budgeted? Risk quantification is the first step if we want to control construction hazards. Uncertainty evaluation can help us to determine many problems. In this case study, we understand what is being controlled clearly, and can ensure a safety boundary. Thus, our measures become more exactly and our options become more accurately. "Opportunistic efficiency" is an interesting concept. The goal is to avoid risk, but, construction work is not gambling. We can get more beneficial effects by determine many cases and understanding uncertainty categories. We make two analyses to prove this notion.

The efficiency of OE in manual excavation after lowering groundwater level

In this manual excavation, because the pit is small, rolling in is unusual. But it is likely that objects will crash. When we use the hazard severity method, it can't consider the different construction methods.

The result shows the rolling in hazard severity, γ=0.102 is larger than the object crashing hazard severity, γ=0.074

We use the OE method by uncertainty analysis we have the hazard index H.I.

The rolling in hazard index H.I. = 1.212 is smaller than the object crashing hazard index H.I. = 1.310.

This means the hazard level is similar when we consider the insurance indemnification ratio Pr.

The rolling in insurance indemnification ratio Pr = 0.446 is larger than the object crashing Pr = 0.062.

When we calculate the OE value the rolling in opportunity efficiency O.E. = 2.716 is larger than the object crashing O.E = 21.129.

Therefore, the safety investment economic consideration used in object crashing is better than the consideration for objects rolling in.

a. The efficiency of OE in mechanical excavation

In mechanical excavation, the retaining piles toppling over are serious hazard. But electric shock is unlikely. If we use the hazard severity method, it can't be considered the different construction methods. The result shows the electric shock hazard severity γ=0.356 is larger than the topping over γ=0.243.

We use the OE method. By uncertainty analysis, we have the hazard index H.I.

The electric shock hazard index H.I. = 3.176 is smaller than the topping over hazard index H.I. = 6.491.

This means the hazard level of toppling over is greater than electric shock hazard level.

When we calculate the OE value the electric shock opportunity efficiency O.E. =20.226 is smaller than topping over crashing O.E = 81.690.

This result is suitable. The safety investment economic consideration used in toppling over is better than the consideration for electric shock.

When the construction method is different, the risk distribution will not be similar, and the safety investment should not be similar too. Without internet, this method is not so easy. It bases on large amounts of classification work. It is possible now by the internet to transfer large information. If we can create nice hazard codes by different construction methods, the risk quality of occupational injury will be developed more accurately.

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Table 1. The working tasks listed by each steps

9 **steps** / Working **Tasks**	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9
1. Site arrangement	*								
2. Equipment preparation	*			*					
3. Set up working canopy		*							
4. Excavate guide pit			*						
5. Excavate soil trash pit			*						
6. Manual excavation					*	*			
7. Send out trash soil						*			
8. Fortify pit wall							*		
9. Low down the steel bar cage								*	
10. Pour the concrete									*

* means the necessary working tasks in this step

Table 2. The possible hazard types listed by each tasks

Working Tasks	**Unsafe behavior**	**Unsafe situation**	**Hazard type**
1. Site arrangement		No suitable site traffic plan	Rolling in, clipping in
2. Equipment preparation	Not using safety gloves	No safety working area	Abrasion
3. Set up working canopy	Not tightening the bearing column & cables	Not keeping the site dry	Toppling over, Objects crashing, Electric shock
4. Excavate guide pit		No suitable excavation procedure	Abrasion
5. Excavate trash soil pit		No suitable excavation procedure	Abrasion
6. Manual excavation	Hammering the gravel without balance	No suitable equipment	Toppling over, Objects crashing, Electric shock
7. Send out gravel	Using windlass incorrectly	No suitable equipment	Toppling over, Objects crashing, Electric shock, Rolling in
8. Fortify pit wall	Hammering the wall surface without balance	No suitable equipment	Toppling over, Objects crashing, Electric shock, Rolling in
9. Low down the steel bar cage	Using windlass incorrectly	No suitable hoisting plan	Rolling in, falling down, Objects crashing
10. Pour the concrete	Excessive vibration, Tremie pipe are not buried inside concrete	No enough bearing equipment	Toppling over

Table 3. The possible hazard list in each step

9 steps / Possible Hazards	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9
1. Rolling in, clipping in	*	*	*		*	*			
2. Falling down			*		*			*	*
3. Electric shock		*		*	*	*	*		
4. Toppling over			*		*	*	*	*	
5. Objects crashing		*	*		*	*	*	*	

* means the possible hazards in this step

Table 4. The statistic data of occupational injuries, 1987~1996, Taiwan.

Possible hazard	Insurance indemnification person-times in 1987~1996 (P_T)				Insurance indemnification moneys in 1987~1997 (P_M) (NTTD/person)				Insurance indemnification averange moneys (NTTD/person)		
	hurt	cripple	dead	subtotal	hurt	cripple	dead	subtotal	hurt	cripple	dead
1. Rolling in, Clipping in	9,152	2,107	43	11,302	54,912	139,062	14,104	208,078	6.0	66	328
2. Falling down	9,936	243	665	10,844	84,456	60,264	218,120	362,840	8.5	248	328
3. Electric shock	708	121	263	1,092	4,390	37,026	86,264	127,680	6.2	306	328
4. Toppling over	604	63	144	811	4,530	12,852	47,232	64,614	7.5	204	328
5. Objects crashing, Slashing	1,889	124	61	2,074	12,656	17,360	20,008	50,024	6.7	140	328
Subtotal				26,123			a	813,236			
	NTTD:Thousands of Taiwan Dollars ; NTTD 1.0 ≒ $ 0.030 U.S.Dollars										

Table 5. The hazard severity coefficient

Possible hazard	cripple severity α	hurt severity β	hazard severity γ	relative hazard severity γ'
1. Rolling in, Clipping in	0.201	0.018	0.056	1.000
2. Falling down	0.756	0.026	0.102	1.817
3. Electric shock	0.933	0.019	0.356	6.351
4. Toppling over	0.622	0.023	0.243	4.327
5. Objects crashing	0.427	0.020	0.074	1.310

Table 6. The physical occupational injuries classification

Grade	Hurt			Cripple			Dead
	1	2	3	4	5	6	7
Condition	Light injury	Hospitalization less than 3 days	Hospitalization over 3 days	Light	Middle	Heavy	

Table 7. The uncertainty analysis index

Probably hazard	Average level	root-mean-square deviation	Injury level		Uncertainty distribution	Uncertainty index
	I_μ	1σ	I_P	I_o	Δ	**U.I.**
Manual excavation after lowing groundwater level						
1. Rolling in, clipping in	2.5	1.5	4	1	1.5	1.00
2. Falling down	3	1	4	2	1	0.67
3. Electric shock	2	1	3	1	1	0.67
4. Toppling over	6	1	7	5	1	0.67
5. Objects crashing	3.5	1.5	5	2	1.5	1.00
Mechanical excavation						
1. Rolling in, clipping in	2	1	3	1	1	1.00
2. Falling down	5	1	6	4	1	1.00
3. Electric shock	1.5	0.5	2	1	0.5	0.50
4. Toppling over	5.5	1.5	7	4	1.5	1.50
5. Objects crashing	3.5	1.5	5	2	1.5	1.50
Manual diving excavation						
1. Rolling in, clipping in	2.5	1.5	4	1	1.5	1.00
2. Falling down	3	1	4	2	1	0.67
3. Electric shock	6	1	7	5	1	0.67
4. Toppling over	6.5	0.5	7	6	0.5	0.33
5. Objects crashing	1.5	0.5	2	1	0.5	0.33

Table 8. The opportunity efficiency of different construction methods

Possible hazard	Relative hazard severity	Uncertainty Index	Hazard Index	Insurance idemnification ratio	Opportunity Efficiency
	γ'	**U.I.**	**H.I.**	Pr	**O.E.**
Manual excavation after lowering groundwater level					
1. Rolling in, clipping	1.000	1.000	1.000	0.256	3.908
2. Falling down	1.817	0.667	1.212	0.446	2.716
3. Electric shock	6.351	0.667	4.234	0.157	26.968
4. Toppling over	4.327	0.667	2.885	0.079	36.307
5. Objects crashing	1.310	1.000	1.310	0.062	21.129
Mechanical excavation					
1. Rolling in, clipping	1.000	1.000	1.000	0.256	3.908
2. Falling down	1.817	1.000	1.817	0.446	4.073
3. Electric shock	6.351	0.500	3.176	0.157	20.226
4. Toppling over	4.327	1.500	6.491	0.079	81.690
5. Objects crashing	1.310	1.500	1.965	0.062	31.694
Manual diving excavation					
1. Rolling in, clipping	1.000	1.000	1.000	0.256	3.908
2. Falling down	1.817	0.667	1.212	0.446	2.716
3. Electric shock	6.351	0.667	4.234	0.157	26.968
4. Toppling over	4.327	0.333	1.442	0.079	18.153
5. Objects crashing	1.310	0.333	0.436	0.062	7.036

Figure 1. “Soil retaining columns”

Figure 2. Cover up working canopy

Figure 3. Set up concrete form work

Figure 4. Mix red soil and making filling balls

Figure 5. Red soil filling balls

Figure 6. Form the red soil pit wall (dry pit)

Figure 7. Diver enter the pit for diving excavation

Figure 8. Diving bell

Figure 9. Send out the trash soil

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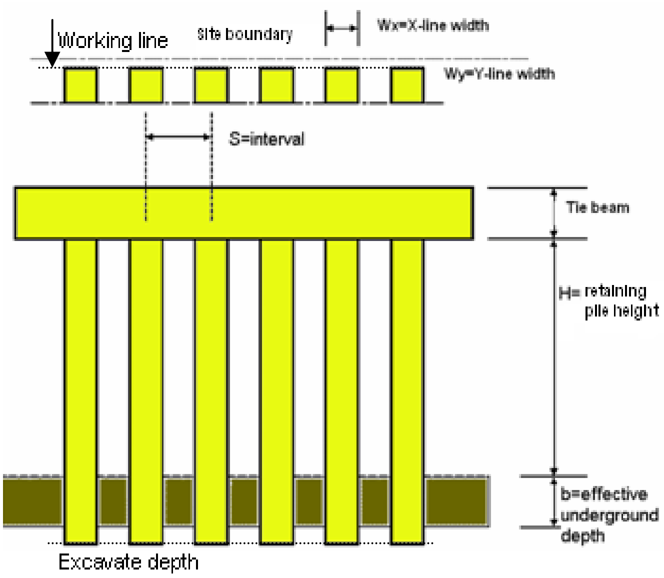

Figure 10. Top & section view pile wall

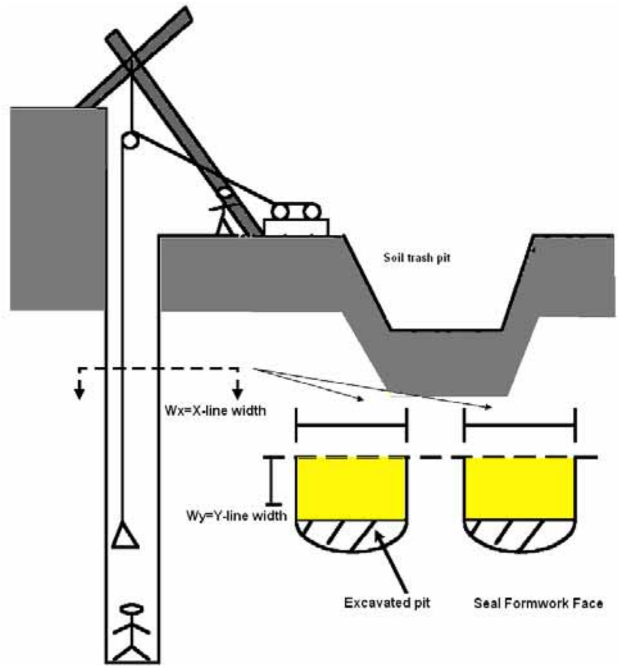

Figure 11. cross section of site & top view of piles

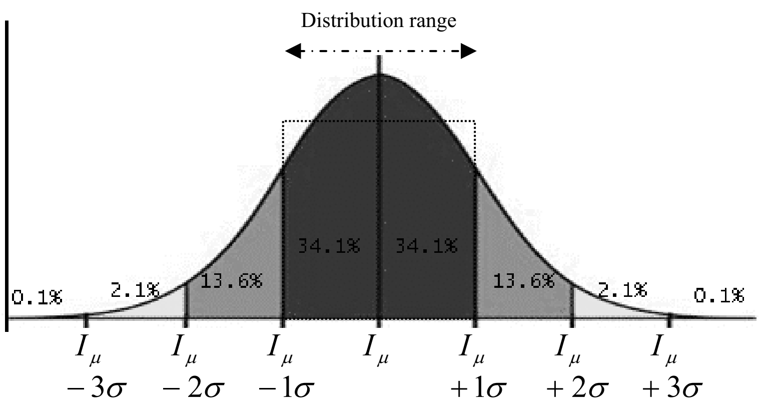

Figure 12. The hazard uncertainty distribution diagram