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Probabilistic assessment of the flood wall at 17th Street Canal, New Orleans

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ABSTRACT: One of the characteristic failures of the flood defense system in New Orleans occurred at the 17th Street Canal. The concrete wall and its extended sheet piles not only failed to withstand against the flood but it was also flushed away by the flood by horizontal sliding. The authors of this paper believe that a probabilistic approach can provide a better understanding of the failure mechanisms, its occurrence probabilities, as well as the consequences of failure of such important infrastructure. In fact, the probabilistic design will show to have several advantages in comparison with deterministic design methods; by applying probabilistic approaches, more careful designs and more cost effective and reliable structures can be constructed. In the present study the probabilistic approach is applied to the 17th Street's flood defense, and its probability of failure under hurricane hazard, considering multiple failure mechanisms is assessed. The Monte Carlo simulation technique together with finite element approach is used for this purpose.

1 INTRODUCTION

1.1 *Lessons after disasters*

The failure of flood defenses in New Orleans and the following events opened a new look at the engineering design of flood protection. The enormous flood events, staying in the minds for years and even generations, gave an important message to the engineers to critically review their designs of flood walls, used until then. Unfortunately, disasters appear always to be the triggering moments for critical evaluation. The Mexico City Earthquake in 1985, for example, addressed the attention of engineers to the behavior of soft soils under peak ground acceleration, and caused geotechnical engineering to be considered much more seriously than before. After the failure of Teton dam in 1976, the piping failure mechanism captured the attention. The flood disaster of New Orleans may lead the engineers to consider flood defenses with improved design methods, based on systematic approaches with probabilistic tools.

1.2 *The failure of flood protection system*

'The System did not perform as a system: the hurricane protection in New Orleans and Southeast Louisiana was a system in name only', (USACE 2006a). Flood protection systems are an example of a series system; if a single levee or flood wall fails, the entire area is impacted. It is important that all components have a common capability based on the character of the hazard they face. The 17th street canal was a part of this system which has absorbed the attention of authors in this research.

Figure 1. Aerial Photograph of the 17th Street Canal Breach (USACE 2006c).

1.3 *The failure of flood wall at the 17th Street Canal*

At about 6:30 AM, with water at elevation 7.0 ft in the 17th Street Canal, the I-wall on the east side of the canal was breached, Figure 1 shows a picture after failure and Figure 2 presents the cross section of the flood wall and its foundation. The breach occurred

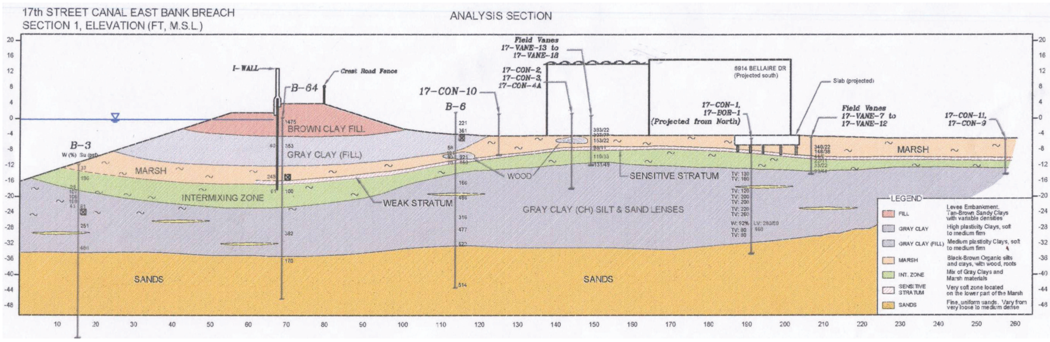

Figure 2. The cross section of the flood wall at 17th street canal and its foundation (Team 2006).

while it was still a few feet to maximum level of the flood wall (USACE 2006a).

The failure of the flood wall in 17th street canal was one of the most famous levee failures in Katrina; but, how predictable it was? In this study it is tried to answer this question by showing up a broader spectrum of possible behavior of the typical I-wall structure. Moreover, it is tried to understand the full performance limits of it and to present new approaches for creating adaptive designs based on physical behavior of engineering components, systems, and parameters variations.

1.4 *The resilient protection system*

'Resilience was not an element in the New Orleans Hurricane Protection System design' (USACE 2006b). Resilient design, by definition of the ability to withstand, without catastrophic failure even in the conditions beyond those intended or estimated in the design, can provide enormous advantages. For instance, as demonstrated in the analysis of Katrina the consequences of this catastrophe could be reduced to approximately less than one-third if the flood wall was designed resilient (USACE 2006d). In fact, on the suggested base of this paper, existing infrastructures or projects can be reviewed to ensure that their original design has not been compromised by changing hazard, changing knowledge base, or variation of relevant elements and their properties.

1.5 *The aims and objectives*

The objective of this research is to provide a better understanding of the behavior of flood defense structures for different load conditions and flood defense asset types. Moreover, it is shown that the probabilistic approach is a more powerful method able to more accurately model the data and provide better understanding of the contribution of every random variable in the final and attended output. This kind of approach, besides, provides a source of information upon which risk management tools and plans.

2 THE PROBABILISTIC APPROACH

2.1 *Introduction and Monte Carlo Method*

Probabilistic approach is the most widely used technique for uncertainty analysis of technical models in which uncertainties are characterized by the probabilities associated with events.

The probabilistic approach in the geotechnical engineering is appreciated. For instance, it helps to integrate analysis of a long levee in one model considering the variation of important parameters. The fluctuation of soil and geometric shapes including the thickness of soil layers, moreover, may be considered in a more advanced modeling.

The Monte Carlo simulation technique used in this study consists of sampling random variables from their statistical distributions and calculating the relative number of simulation for which the limit state is less than zero.

2.2 *Limit state functions*

A simple statement of a a system's failure, described in Equation 1, is called limit state function presenting the resistant function, R, minus the stresses (loading) function, S.

$$Z = R(r_1, r_2, ..., r_i) - S(s_1, s_2, ..., s_j) \tag{1}$$

It is always preferred to define an explicit limit state function in order to get the probability of failure in the form of Equation 1. However, an explicit function can not be always applied; in fact it can be defined in simple problems not for complicated ones. For instance, the estimation of probability of sliding of the 17th street flood wall is a very complicated process which can not be modeled with an explicit limit state function; therefore, a finite element approach is used in this study to estimate its failure modes; in other words, an implicit limit state function is used to estimate its probability of failure.

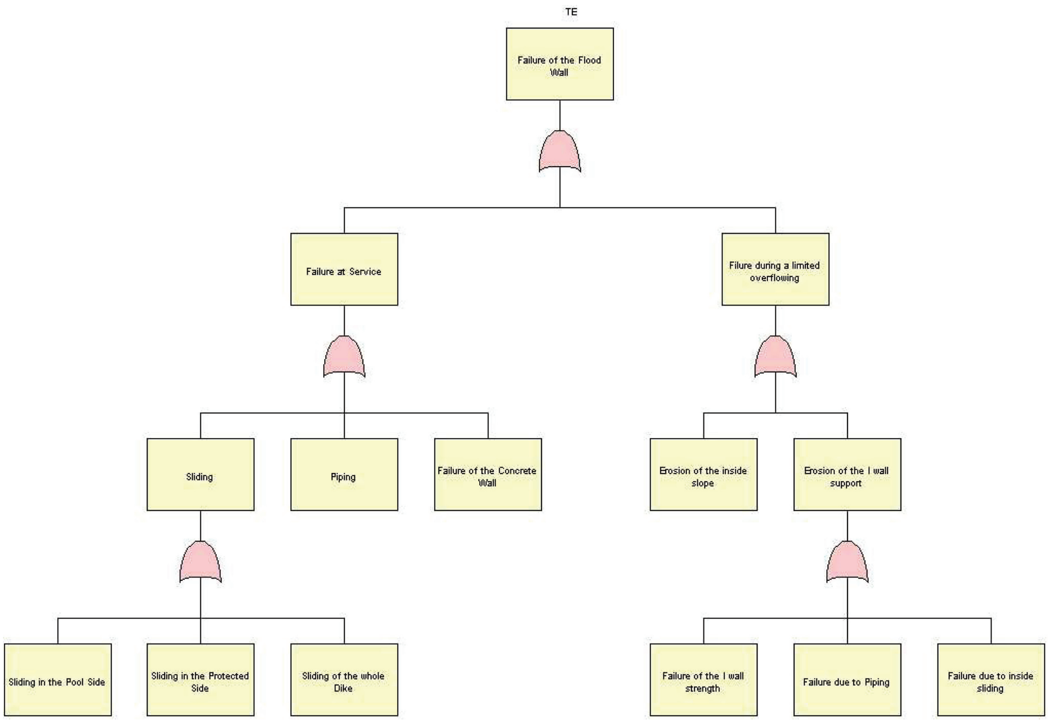

Figure 3. The fault tree of most expected failure mechanisms for the 17th street flood wall, New Orleans.

3 THE FAILURE SCENARIOS

3.1 *The fault tree*

The main function of designed flood wall in the 17th street canal was protection of the city from flooding; therefore, its failure to do this job is the top event as presented in the fault tree of Figure 3.

In this figure, there are two main intermediate events showing the importance of reliability analysis in two modes: expected and extreme conditions; in other words, a flood defense system should be stable with the expected loads and able to tolerate the overtopping or overflowing for the expected time. This means that a good design should enjoy the resiliency as it was explained in 1.4; to highlight the importance of overflowing condition, more details are discussed in 3.4.

The main intermediate events for the expected conditions in Figure 3 are the sliding, piping, and failure of concrete wall. The sliding is the main mechanism for the failure of the 17th street flood wall, therefore, here it is concentrated on this case; the other failure modes, nevertheless, are shortly discussed.

3.2 *The sliding*

In the present research, it is attended to the most important failure mode, sliding, by the finite element approach in a probabilistic way. It is proved by the previous researches that the main failure mechanism was sliding (USACE 2006d). Therefore, the concentration is on the sliding as it is discussed from Section 4.

3.3 *The piping*

It is concluded that the failure of 17th street canal was not conducted by piping or seepage (Team 2006); in this study, therefore, the probability of failure by seepage is not discussed in detail; however, there are explicit (analytical) limit state functions which can be approximately used to evaluate the probability of piping which might be a case for further research (Number 2006).

3.4 *The overflowing condition*

In the design phase or reliability assessment of a flood defense, the expected time of overflowing should be attended seriously. In other words, an infrastructure like a flood defense should be able to sustain the overflowing conditions to provide us the resiliency discussed in Section 1.4. For instance, by overflowing over the 'I wall', its support maybe scoured and eroded as presented in Figure 4; therefore, the probability of both structural and foundational failure increases. Furthermore, the overflowing may cause the erosion of the slope which encourages the probability of sliding. Meanwhile, the structural system should be able to tolerate more moment as a result of decreasing the support. This factors are shown in the right side of the Figure 3.

4 INPUT PARAMETERS AND MODELING

4.1 *The main resistance parameters*

The variation of soil parameters are considered in a finite element model of 17th street flood wall. Those are ten soil parameters which vary both in horizontal and vertical directions as presented in Table 1. The geotechnical data are extracted from the several hundreds of pages of the previous researches conducted by American Corps of Engineers (USACE 2006c) and Independent Levee Investigation Team (Team 2006). All the parameters are assumed to be normally distributed, and the related coefficients of variation of soil layers are concluded from the same sources or the experience.

Figure 4. Scour and Erosion on the Protected Side of the IHNC, New Orleans (USACE 2006c).

4.2 *Loads*

Here, it is tried to estimate the probability of failure of the 17th street flood wall for different water levels. Therefore, the probability of failure, P_f, is estimated for the normal water level and five other higher levels: MSL +4, +6, +8, +10, and +12 feet.

It is, also, advised for reliability analysis of flood defenses during overflowing that the, P_f, also be calculated for a higher level, as it was previously discussed in 3.14.

4.3 *The modeling and validation*

A finite element program, Plaxis, is used to analyze the behavior of the of the 17th street flood wall considering different water levels. The flood wall is modeled based on the geometry depicted in Figure 1 as it is used by Independent Levee Investigation Team **??**. Figure 5 presents this model which is supposed to be used thousands of times for estimation of the reliability of the flood wall. A short summary of this model, also, is presented in the Table 2.

The Mohr-Columb and Advanced Soft Soil models are used for the prediction of soil's behavior and estimation of safety. It is preffered to mainly use Mohr-Columb criteria to reduce the calculation time; considering the fact that the more advanced models are more time consuming; besides, Mohr-Columb Model gives good results for failure prediction.

The safety factor is defined as a ratio between resistant forces over the stresses, $F_s = \frac{Resistance}{Stress}$. Therefore to calculate the safety factor, the resistant soil parameters are reduced with the same ration step by step till

Table 1. The variation of soil parameters considered in the probabilistic finite element analysis.

	Soil	Model	Behavior	Distribution Type	Parameter	CV[1]
1	Brown Clay	Mohr-Coulomb	Undrained	Normal	Cohesion (C)	0.2
2	Gray Clay	Mohr-Coulomb	Undrained	Normal	Cohesion (C)	0.2
3	Marsh Under Levee	Mohr-Coulomb	Undrained	Normal	Cohesion (C)	0.2
4	Marsh Free Field	Mohr-Coulomb	Undrained	Normal	Cohesion (C)	0.2
5	Sensitive Layer-Under Levee	Mohr-Coulomb	Undrained	Normal	Cohesion (C)	0.15
6	Sensitive Layer-Free Field	Mohr-Coulomb	Undrained	Normal	Cohesion (C)	0.15
7	Intermix Zone	Soft Soil Model	Undrained	Normal	Friction Angle(ϕ)	0.15
8	Gray Clay Horizontal	Mohr-Coulomb	Undrained	Normal	Cohesion (C)	0.15
9	Gray Clay Vertical	Mohr-Coulomb	Undrained	Normal	Cohesion (C)	0.15
10	Sand	Mohr-Coulomb	Drained	Normal	Friction Angle(ϕ)	0.1

[1] CV is the coefficient of Variation.

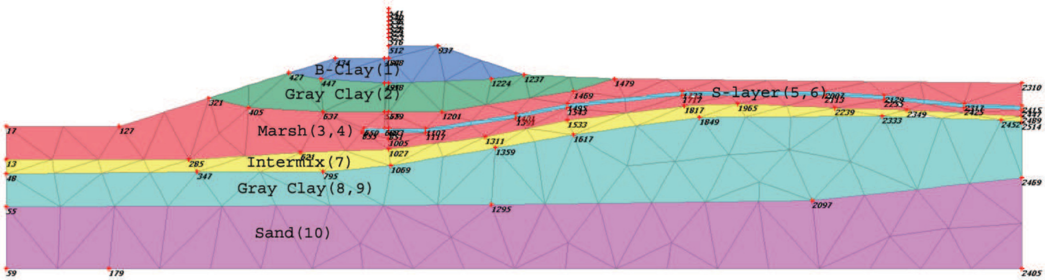

Figure 5. Plot of the finite element model for 17th street flood wall and its foundation, modeled with Plaxis.

Table 2. Numbers and type of elements used in the 17th street canal model.

Type	Type of element	Total no.
Soil	15-node triangle	289
Plate	5-node line	14
Interface	5-node line	19

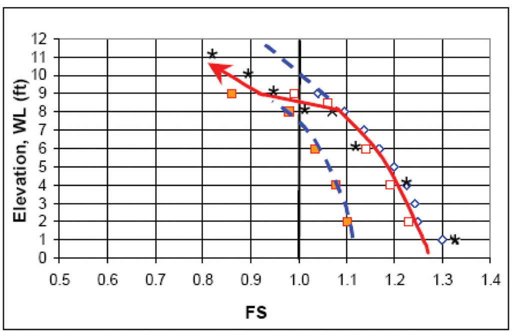

Figure 6. Calculated Safety Factors for three models based on Plaxis analysis of the 17th Street Canal breach (Team 2006), squares, in comparison with the results of the model used in this research, shown by stars.

the failure of model. Then the ration between the first value and the reduced one defines the safety factor.

Figure 6 presents a comparison between the result of the model used in this research by the models of Independent Levee Investigation Team (Team 2006). The stars, *, in this figure are the calculated safety factors by mean value of resistant parameters introduced in Table 1. A well correspondence of the stars and the other (squared) points can be observed in this figure.

4.4 *Typical results*

The analysis of the model with mean values, called typical result, is presented in Figure 7; this plot shows deformation of flood wall and its foundation as a result of loading in MSL +8 feet; and, the $\phi - c$ reduction technique has been used to plot the most probable scenario as it is shown in the figure.

5 PROBABILISTIC FINITE ELEMENTS

The probabilistic analysis needs a lot of calculations; therefore, a program is written to interactively work with Plaxis. In this case, it take the control of Plaxis, feeds the Plaxis with the desired probability density function of assumed parameters, invokes the software to calculate the different adapted phases, and finally gathers the safety factors and correlated variables. Then, the probability of failure for the expected conditions can be calculated. In fact, this automatic procedure makes us enable to get a broader spectrum of physical behavior and better understanding of engineering components and the effects of their variations.

The main advantage of this approach is the mobile failure mode; the failure shape varies with the variations of parameters. This is possible by using the $\phi - c$ reduction technique which reduces the resistant parameters with the same ratio in an step by step procedure. In fact, by every variation of soil parameters a new problem is defined and solved. For instance, by variation of the clay parameters in the foundation, the shape, curvature, and depth of sliding are adapted.

However, this is still a time consuming process that might be accounted as a disadvantage; nevertheless, it can be improved by implementing response surfaces or importance sampling methods (Waarts 2000).

6 CALCULATED SAFETY FACTORS

6.1 *Variation of safety factors*

As a result of implementing the $\phi - c$ reduction technique, the safety factors of slope sliding in finite element analysis are calculated; then thousands of finite element calculations are done to get an acceptable estimation of Probability of failure, P_f. Figures 8

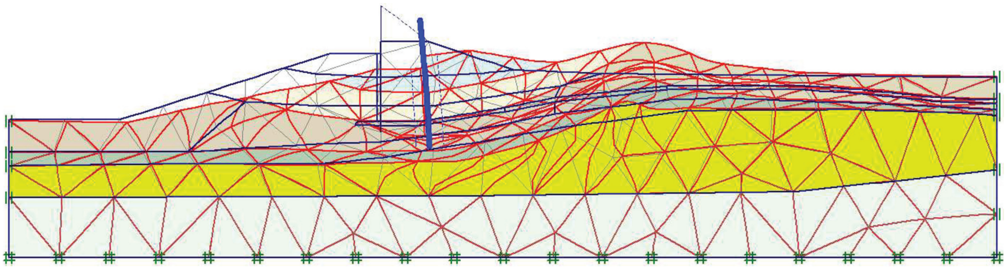

Figure 7. The plot of typical deformation of the 17th street canal modeled with Plaxis.

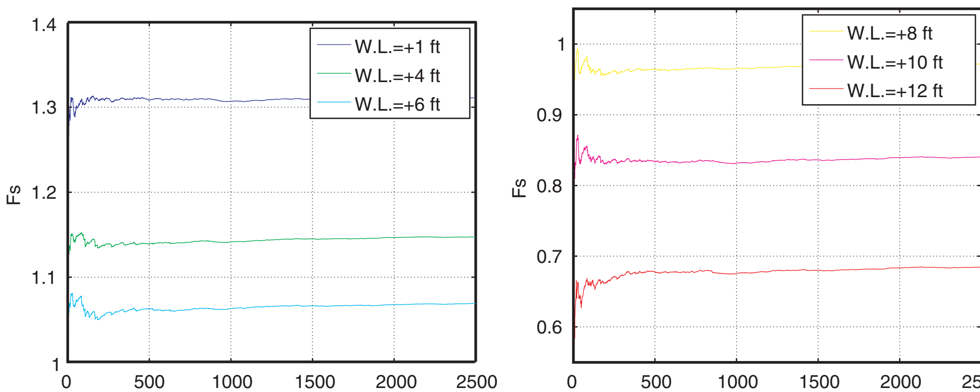

Figure 8. Plots of mean value of Safety Factors versus the Number of Finite Element Analysis for six different water levels for the 17th street flood wall.

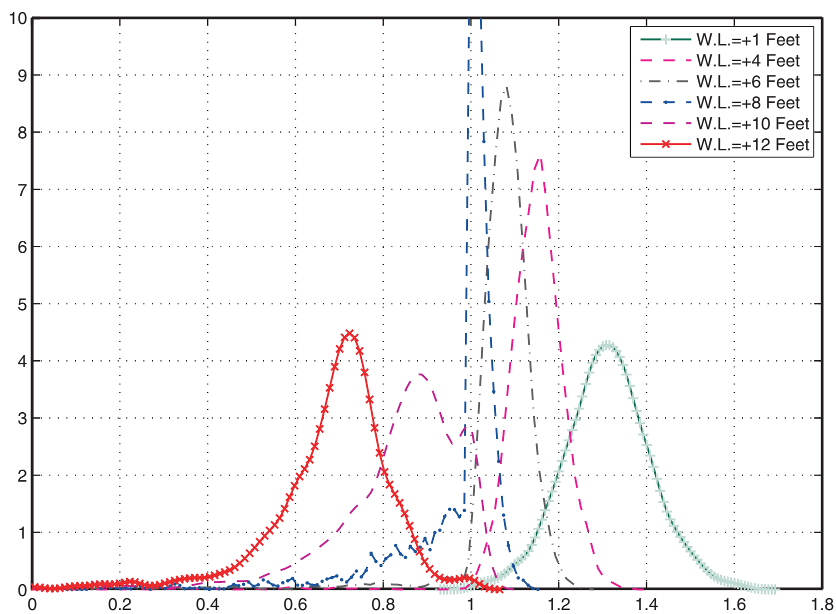

Figure 9. The plot of PDFs of Fs for different water levels; the plots show the probability of failure of the 17th street flood wall, New Orleans.

shows mean values of safety factors regarding the number of calculations for different water levels.

On the other hand, since the $\phi - c$ technique is applicable for the stable models, the percentage of loading has been considered as a parallel definition of the safety factor when it is less than one; this parameter is introduced as SUM(M-stage) in Plaxis. It is not, therefore, the true value of safety factor; but, it is a good representative for it when the safety factor is below one.

6.2 *The PDF of safety factors*

Having the calculated safety factors presented in Figure 8, the probability distribution function, PDF, of safety factors are plotted regarding the different water levels for the 17th street flood wall in Figure 9 and the probability of failure is calculated. The integration of area less than one presents the probability of failure; it is the reason that by increasing the water level behind flood wall, the pdf of safety factors move toward smaller values.

It should be remarked that the number of calculation (N) for getting an accurate result can be estimated by Equation 2. In other words, to get the real value of P_f in the first couple rows of Table 3, more calculation is needed.

Table 3. The probability of failure estimated in different water levels for the 17th street flood wall, New Orleans. N_f^*: is the number of failures. **: More calculations are needed to accurately estimate P_f.

	N	W.L. (ft)	P_f	N_f^*	$N \geq$
1	2500	+1	**	1	100,000
2	2500	+4	**	24	41,000
3	2500	+6	**	115	8,300
4	2500	+8	0.28	729	970
5	2500	+10	0.90	2345	30
6	2500	+12	0.99	2495	1

$$N \geq 400 * (\frac{1}{P_f} - 1) \tag{2}$$

6.3 *The contribution of soil layers*

The contribution of every variable, X_i, in level III-calculation can be established according to the Equation 3 in which the coefficient of variation of X_i regarding the limit state function, Z, is calculated. On the base of this equation, the contribution of the variables of Table 1 are presented in Figure 6.3; it is clear that the Marsh layer and Gray Clay layer have the biggest contribution.

$$\alpha_i = \rho_{X_i,Z} = \frac{Cov(X_i, Z)}{\sigma_{X_i}.\sigma_Z} \tag{3}$$

7 CONCLUSIONS

In the present study, it is tried to introduce a probabilistic method integrated with finite element analysis to accurately estimate the probability of failure of flood

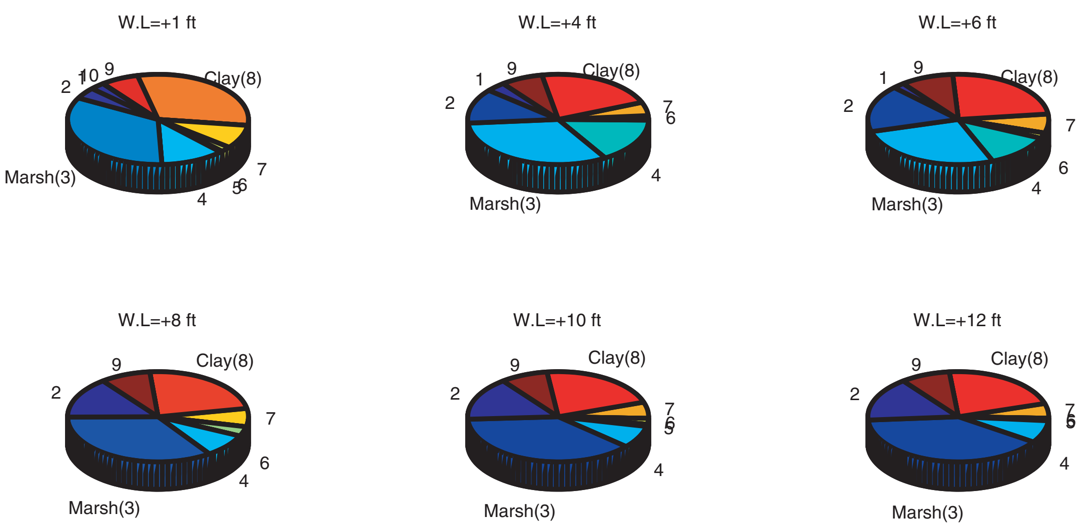

Figure 10. The contribution of different variable parameters (in Table 1) on the probability of failure of the 17th street flood wall, New Orleans; the labels or numbers are according to the Table 1. Every figure is related to a specified water level.

defenses. The behavior of the 17th street flood wall as a case study is investigated by this method.

It is concluded that the probability of failure was very high in the 17th street flood wall of New Orleans.

The presented approach is a time consuming process that might be considered as a disadvantage; nevertheless, it can be improved by implementing of the advanced level three methods such as response surface, importance sampling, or directional adaptive response sampling methods.

The resiliency of the flood defenses should be taken into account in design process; it means that if the overtopping or overflowing occurs, the structure should sustain overloading for a certain time.

8 RECOMMENDATIONS

This research provides a very flexible and accurate approach for safety assessment of flood defenses; it is strongly recommended using this technique to estimate the safety of flood defenses including dikes and levees.

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