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STABILITY ANALYSIS OF A SILICA SAND SLOPE MODEL SUBJECTED TO SURCHARGE LOAD USING LEM AND FEM METHODS

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ABSTRACT: Natural disasters such as landslides are frequent occurrences around the world. Despite the many studies conducted on slope behavior, the loss of countless lives and valuable property continues. This study employed the Limit Equilibrium Method (LEM), simulated using SLOPE/W software, based on the Mohr-Coulomb failure criterion to examine the behavior of a silica sand slope under surcharge load. The properties of silica sand, such as dry unit weight (γ_d), saturated unit weight (γ_{sat}), angle of internal friction (φ), and soil cohesion (c), were determined through compaction and consolidated-drained (CD) triaxial tests. The computed Factor of Safety (FOS) value from the SLOPE/W analysis is 0.955 at an applied surcharge load of 6.4 kPa. The result was then compared with Finite Element Method (FEM), simulated using Plaxis 3D software based on Strength Reduction Method under the same loading conditions. The results from both analyses showed that the Plaxis 3D analysis generally gave a higher FOS value (6.321) compared to the FOS value obtained from the SLOPE/W analysis (0.955). The shape and critical slip surface are almost identical for each analysis. The results of both numerical simulations were then compared to the experimental testing. The LEM method provides a more realistic indication of FOS. A clear understanding of the approach employed in the LEM and FEM analyses determines the validity of the analysis carried out.

Keywords: Slope stability analysis, SLOPE/W, Plaxis 3D, Silica sand, Surcharge load

1. INTRODUCTION

The global prevalence of slope failure has attracted the interest of many engineers and researchers. Slope failure is described as the movement of soil and rocks down a slope by the force of gravity on either natural or man-made slopes [1]. These occurrences are one of the well-known geological hazards that have caused many fatalities and economic losses due to their unpredictable nature [2,3].

Among the factors influencing slope failures are the complexity of the slope-forming materials, geological and hydrological conditions, and anthropogenic activities. According to Mizal-Azzmi et al. [4] and Paul et al. [5], among others, surcharge loads have a significant influence on slope stability because they add gravitational force to the soil, which causes shear stress increase exceeding than the shear strength of soil. Jelani et al. [6] reported that slope failure may occur when there is an excessive surcharge load imposed on the slope crest.

It is crucial to determine the stability of slopes subjected to surcharge load to evaluate the slope stability. The factor of safety (FOS) is frequently used to measure slope stability. It is computed based on the ratio of the resisting forces (R_f) to the driving forces (D_f), as shown in Eq. (1). Slopes with FOS values less than 1.0 are categorised as unstable.

$$\text{FOS} = \left(\frac{R_f}{D_f}\right) \tag{1}$$

There are two approaches in slope stability analysis which are empirical and numerical analyses [7,8]. Due to the advancement of computer technology, researchers and engineers are gaining more interest in numerical simulation methods to predict slope behaviour [9,10]. According to Salunkhe et al. [11], the two methods often used in slope stability analyses are Limit Equilibrium Method (LEM) and Finite Element Method (FEM).

LEM has been the most popular approach for resolving geotechnical engineering problems because of its simplicity and precision [12,13], and it only requires a simple Mohr-Coulomb soil model. The estimation of factor of safety carried out with LEM is likely to be always give higher estimation of FOS.

FEM is the most utilized numerical method in practical applications due to its ability to simulate deformations and provide reliable predictions of the soil-structure interaction. However, the effectiveness relies on the condition that the analysis correctly and precisely simulates the different construction phases and material behavior [14,15]. FEM calculates the FOS by employing the strength reduction method and analyzing the deformations of the slope model subjected to surcharge load [16]. The strength reduction method continuously reduces the strength parameters of soil body until equilibrium is no longer possible and failure takes place. The FOS will be calculated as the initial shear strength over the shear strength at failure [17]. This method also adheres to the equilibrium and compatibility equations from elasticity theory, making it a more mathematically rigorous approach. Additionally, it allows for the determination of displacements, stresses, and strains at various nodes within the slope domain. These advantages highlight some of the additional benefits of using the FEM.

However, unlike LEM, which requires a simple Mohr-Coulomb soil model, FEM requires a comprehensive stress-strain model for the soil. In addition, the key difference between the two analytical methods is that LEM is based on static equilibrium while FEM utilizes the stress-strain relationship or constitutive law [18]. Table 1 summarizes the comparison of LEM and FEM.

This study employed the LEM (SLOPE/W) and FEM (Plaxis 3D) numerical simulation software to perform the slope stability analysis of silica sand subjected to a surcharge load. The Mohr-Coulomb soil model [19,20] was employed in SLOPE/W to obtain the expected failure surface and the corresponding safety factor. The Morgenstern-Price method was utilised to improve the accuracy of slope stability analysis. In contrast, the slope stability analysis with Plaxis 3D used a similar Mohr-Coulomb model with Strength Reduction Method [21-24] to compute the FOS and deformations value. The obtained FOS and slip surface were compared for validation purposes.

2. RESEARCH SIGNIFICANCE

This study aims to analyze the stability of a silica sand slope subjected to a surcharge load and compare the FOS value, as well as the shape and position of the critical slip surface for the proposed soil slope model. Two different geotechnical software, namely SLOPE/W for LEM and Plaxis 3D for FEM were used to calculate the FOS value. This study's findings may assist engineers and researchers, especially in geotechnical field, to choose the appropriate model for predicting slope failure.

3. MATERIALS AND METHODS

The silica sand properties were obtained from the standard proctor test and consolidated-drained (CD) triaxial compression test at three different effective confining pressures of 50 kPa, 100 kPa and 200 kPa, previously conducted by Ishak et al. [25] as shown in Fig.1. The laboratory test results were used in SLOPE/W and Plaxis 3D to analysis slope behaviour when subjected to surcharge load.

3.1 Laboratory Test

The slope stability analysis in SLOPE/W requires three input parameters for the Mohr-Coulomb soil model that includes dry unit weight (γ_d), angle of internal friction (φ) and the cohesion of soil (c). Whereas the Plaxis 3D software requires seven input parameters such as the reference secant stiffness modulus (E_{50}^{ref}), effective friction angle (φ'), effective dilation angle (ψ'), saturated unit weight (γ_{sat}), dry unit weight (γ_d), cohesion of soil (c) and coefficient of earth pressure at rest (K_0), as tabulated in Table 2.

Table 1 Summary of differences between LEM and FEM [12-15]

No	Criteria	LEM	FEM
1	General criteria	Among the most popular method due to its simplicity and accuracy	The analysis is based on computer performance. It can simulate complex geometry problem with various analysis
2	Critical surface determination	The critical surface is search using geometry	Automatically determine by the software
3	Soil model	Various soil models available, the simplest is Mohr-Coulomb. The soil model using static equilibrium	The soil is modelled using a strength reduction method. Require stress-strain relationship to model the soil behavior
4	Displacement measurement	This method unable to measure the displacement	Able to determine the deformation
5	Progressive failure	Unable to model progressive failure	Able to model progressive failure
6	Method of calculation	The slope is divided into finite vertical slices	The soil is divided into several mesh elements

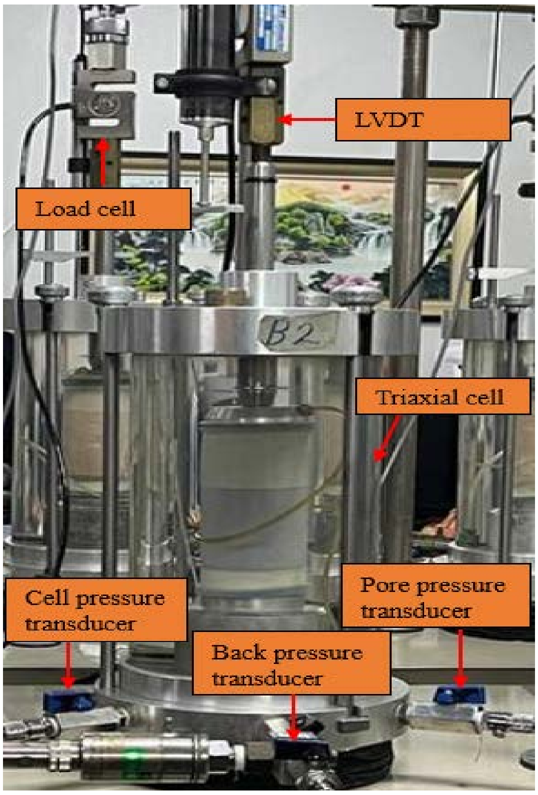


Fig. 1 Laboratory test setup for CD triaxial compression test

Table 2 Mohr-Coulomb model input parameters for silica sand

Parameters required	Mohr-Coulomb-(SLOPE/W)	Mohr-Coulomb (Plaxis 3D)
E_{50}^{ref} (kPa)	-	36798
γ_{sat} (kN/m^3)	-	17.89
γ_d (kN/m^3)	15.33	15.33
φ (°)	30	30
ψ (°)	-	0.7
c (kPa)	17.5	17.5
K_0	-	0.3572

3.2 LEM and FEM Analysis

The concepts and principles of the SLOPE/W application for slope stability analysis are based on LEM. According to Krahn [19], the programme calculates the FOS for various shear surfaces, including circular, non-circular and defined surfaces. This study employed the Morgenstern-Price method because it can satisfy the static equilibrium requirements [26]. The study also used the Mohr-Coulomb input parameters and a half-sine function for inter-slice forces to calculate the FOS based on the critical slip surface identified using the entry and exit option.

In contrast, Plaxis 3D is a specialised three-dimensional finite element analysis capable of performing slope stability of soil and rock materials [27]. It can deal with complex geotechnical problems, including soil deformation and stresses [28,29]. The Mohr-Coulomb parameters served as the input for the slope stability analysis.

The Plaxis 3D slope stability analysis consists of four phases comprising of the initial, excavation, surcharge, and safety. The soil materials of the slope model were activated in the initial phase, and the excavated soil volume was deactivated during the excavation phase. In the surcharge phase, a surcharge load was applied on top of the slope, and finally, the safety phase was activated to calculate the FOS of the soil slope model.

The proposed geometric configuration of the simulated slope model analysed by both simulation software has a fixed dimension of 1.2m high, 0.5m wide and 3.5m long, forming slope inclination angle approximately 34°. The surcharge load applied to the top of the slope was 6.4 kPa to determine the FOS and the slip surface, which will be discussed in the next section.

4. RESULTS AND DISCUSSION

4.1 Laboratory Test Result

Standard proctor test

Fig.2 shows the result of the standard proctor test. The silica sand has a maximum dry unit weight, γ_d, of 15.33 kN/m^3 at an optimum moisture content, *w* of 16.7%. The result is consistent with the findings published by [30]. The dry unit weight, γ_d, was obtained using Eq. (2). The value of *Gs* is 2.62 g/cm^3.

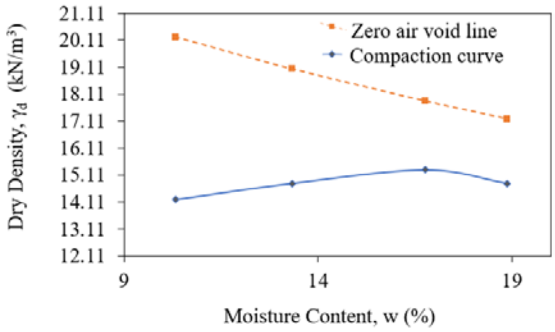


Fig.2 Standard proctor test result.

$$\gamma d = \left(\frac{\gamma sat}{1+w}\right) \quad (2)$$

Consolidated-drained (CD) triaxial test

The values of the soil cohesion, *c*, and angle of soil friction, φ, were obtained from the graph of *s-t* plot, as shown in Fig.3. The *c* and φ values were 17.5 kPa and 30° respectively. The *s* and *t* values were calculated from the major and minor principal stress obtained from CD triaxial compression tests given in Table 3, by using Eq. (3) and Eq. (4).

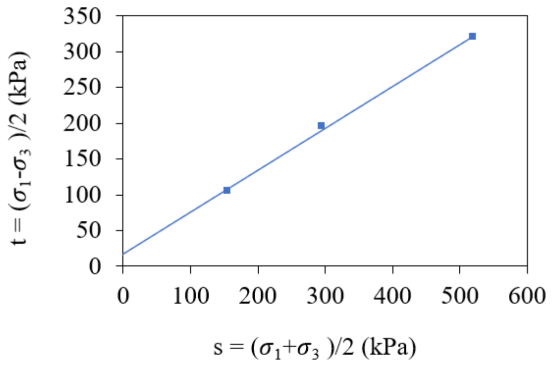


Fig.3 Shear strength of silica sand determined from s-t plot

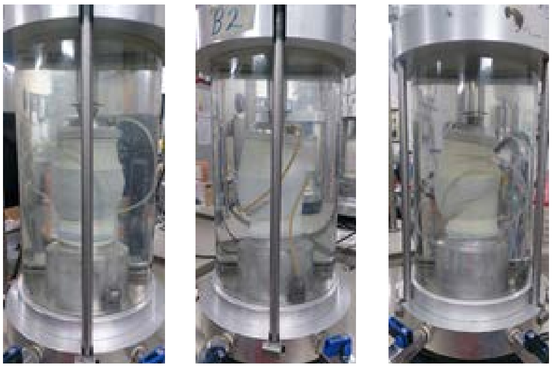
Table 3 Parameters for the silica sand from the CD triaxial test

Specimen	Minor principal stress, σ'_3 (kPa)	Major principal stress, σ'_1 (kPa)
A	50	260.43
B	100	491.13
C	200	839.68

$$s = \left(\frac{Major\ stress, \sigma_1 + Minor\ stress,\ \sigma_3}{2}\right) \quad (3)$$

$$t = \left(\frac{Major\ stress, \sigma_1 - Minor\ stress, \sigma_3}{2}\right) \quad (4)$$

The soil sample's final conditions after the CD triaxial compression test at different confining pressures of 50 kPa, 100 kPa and 200 kPa are shown in Fig 4.



(a) (b) (c)

Fig.4 The final conditions of the sand specimen after failure at (a) 50 kPa (b) 100 kPa (c) 200 kPa

Fig.5 shows the determination of the dilatancy angle based on the gradient of volumetric-axial strain curve. The selected dilatancy rate, *d* value was determined from the confining pressure of 50 kPa because it has gentle slope gradient than the others. The *d* value of 0.0236 was used in Eq. (5) to calculate the dilatancy angle, ψ [31], which was 0.7°.

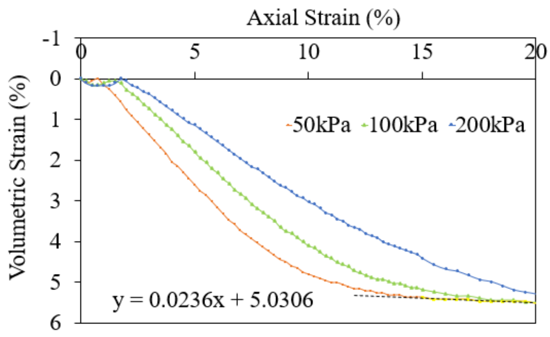


Fig.5 Determination of the dilatancy angle

$$\psi = \left(\frac{-sin^{-1}}{\frac{d}{2-d}}\right) \quad (5)$$

Evaluation of soil stiffness parameter for silica sand

The CD triaxial test is used to determine the soil stiffness parameter called the reference secant stiffness, E_{50}^{ref}. Figure 6 shows the deviatoric stress-strain curve for the three confining pressures of 50 kPa, 100 kPa, and 200 kPa. The stress-strain behaviour for primary loading of silica sand is highly non-linear. Figs. 7-9 show the determination of the confining stress dependent stiffness modulus, E_{50} for confining pressures of 50 kPa, 100 kPa and 200 kPa. The values of E_{50} are 28404 kPa, 32138 kPa and 54929 kPa for the respective confining pressure. The calculated average E_{50}^{ref} is 36798 kPa, determined from the average values of a total of three soil testing by using Eq. (6). The *m* value used in this study is 0.5.

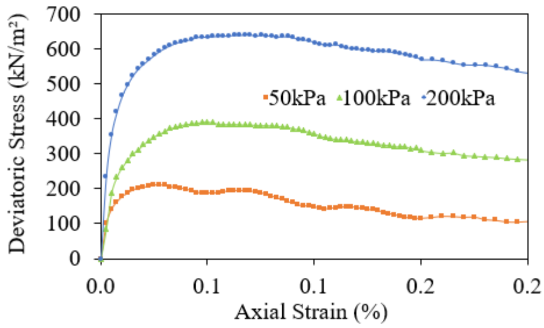


Fig.6 The graph of stress-strain curve

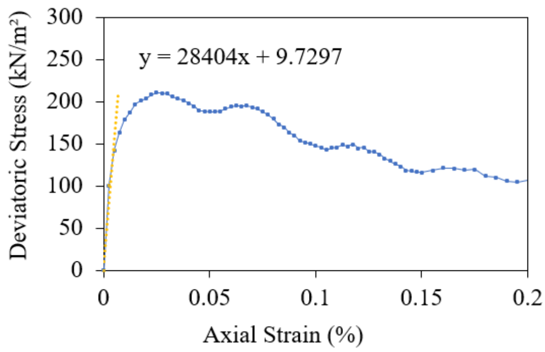


Fig.7 Determination of the E_{50} moduli at 50 kPa

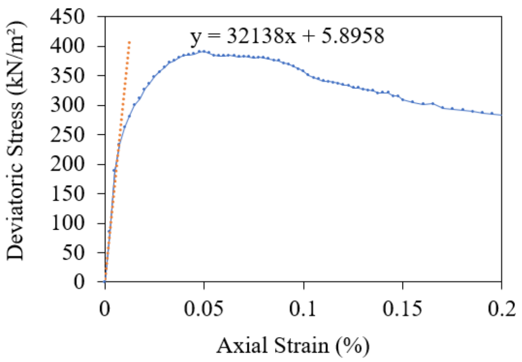


Fig.8 Determination of the E_{50} moduli at 100 kPa

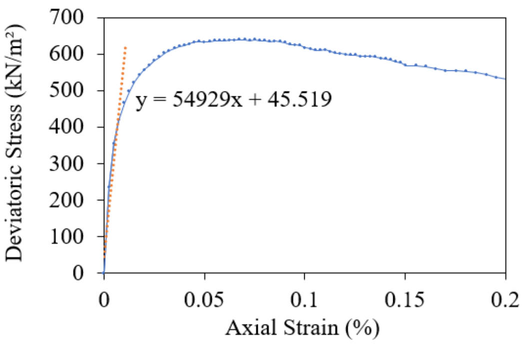


Fig.9 Determination of the E_{50} moduli at 200 kPa

$$E_{50^{ref}} = \frac{E_{50}}{\left(\frac{(\sigma'3 + c\cot\emptyset)}{(100 + c\cot\emptyset)}\right)^m} \quad (6)$$

4.2 Numerical Simulation Analysis

The Morgenstern-Price method in the SLOPE/W considered moment and force equilibrium of the sliding mass while determining FOS of a slope. Entry and exit approach is used to determine the critical slip surface based on entry point, exit point and tangent point.

Fig.10 shows that the FOS value from the SLOPE/W analysis was 0.955, while Fig.11 shows that the value of FOS from the Plaxis 3D analysis was 6.321. By comparing both analyses, the SLOPE/W gave a smaller FOS value.

The difference in the FOS values of the SLOPE/W and Plaxis 3D analyses was because the LEM analysis was based on force equilibrium and does not consider the stress-strain relationship, while the FEM applied the stress-strain relationships. The basic assumption for LEM is that the FOS reflects an average of the assumed slip surface and is the same at all points along the slope surface, whereas the FEM analysis determined the FOS using a shear strength reduction technique.

Furthermore, the sliding mass in the LEM analysis was divided into finite vertical slices to refine the slope stability analysis. The shear and interslice forces were calculated, and the appropriate force or moment equilibrium was fulfilled for the static equilibrium conditions required to calculate the FOS and stress for each slice of the assumed slip surface.

On the contrary, the FEM analysis divided the soil model into several mesh elements. The constitutive laws for the materials in the slope stability model were used to compute the stresses and strains. The slope failure occurred naturally in the zones where the soil shear strength failed to sustain the applied shear stresses.

The fundamental difference between the basic principles of LEM and FEM analyses explains the difference between the computed FOS. The difference in the FOS values from LEM and FEM is due, for the most part, to the normal stress distribution along the critical slip surface, which occurs primarily in the toe area of the slope model. The LEM analysis computed the FOS for each element along the critical failure surface, unlike the FEM analysis, which computed a weighted average of FOS.

Given the results, there are advantages and drawbacks to using LEM and FEM to perform slope stability analysis to determine the FOS and slip surfaces. LEM requires minimal input parameters, making it easier to use and practical. On the other hand, FEM can handle the soil's stress-strain behavior and more complex conditions, resulting in a more realistic stress distribution. However, FEM analysis requires slightly more input parameters than the LEM.

With an understanding of the different analysis approaches in using LEM and FEM, it is prudent to employ a suitable method based on the nature and purpose of slope stability analysis. In this study, the LEM method proved to be more realistic indicator of FOS, similar to the findings reported by [32].

The shape and position of the critical slip surface produced by the SLOPE/W and Plaxis 3D analyses were almost identical. The critical slip surface intersects at the crest and the toe of the slope, indicating a toe failure.

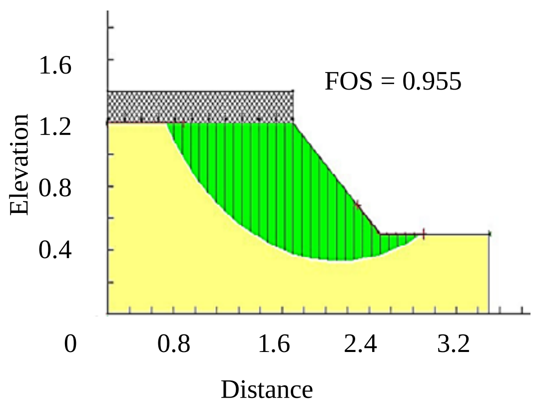


Fig.10 Results of the SLOPE/W analysis for silica sand subjected to surcharge load.

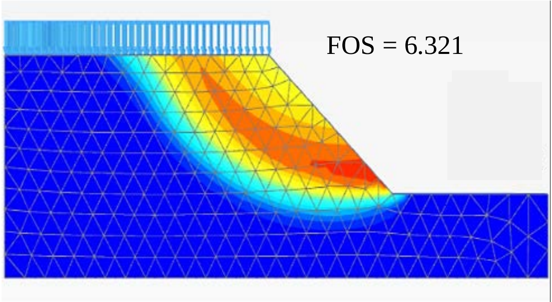


Fig.11 Results of the Plaxis 3D analysis for silica sand subjected to surcharge load.

4.3 Validation of the Numerical Simulations with Experimental Test Results

The results of numerical simulations were validated with a small-scale experimental test, as shown in Fig.12. A similar surcharge load was applied to the soil slope model. The experimental results revealed that the load application caused the slope to fail. Therefore, the LEM method provided a more realistic indication of the FOS, with a value of 0.955.

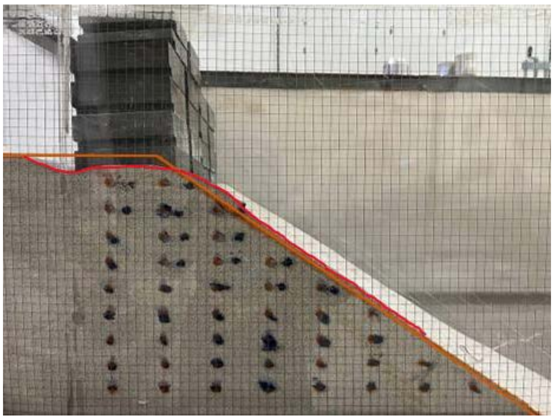


Fig.12 Slope failure after application of similar surcharge load.

5. CONCLUSION

This study has analysed the slope stability of silica sand subjected to surcharge load by employing two commonly used geotechnical software programs, namely SLOPE/W based on LEM and Plaxis 3D based on FEM. The SLOPE/W and Plaxis 3D analyses used the Mohr-Coulomb soil model as input parameters. The two main behaviours observed in this study were the FOS and critical slip surface. The FOS from the SLOPE/W and Plaxis 3D analyses when applying a 6.4 kPa surcharge load were 0.955 and 6.321. The results from both analyses showed that the Plaxis 3D analysis generally gave a higher FOS value (6.321) compared to the FOS value obtained from the SLOPE/W analysis (0.955). The shape and critical slip surface are almost identical for each analysis. The results of both numerical simulations were then compared to the experimental testing. The LEM method provides a more realistic indication of FOS. A clear understanding of the approach used in the LEM and FEM analyses determines the validity of the analysis carried out.

6. ACKNOWLEDGMENTS

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