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Stability Analysis for Design of Earth Fill Dam

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The increased development and population expansion in urbanize area in Malaysia have created a need to construct an inter-basin water transfer tunnel to fulfill the demand of water in the water scarced region. As one of the main components in the Pahang-Selangor Raw Water Transfer Project, the Kelau Dam was designed to serve as a regulating dam in order to maintain a sufficient water level in the Kelau River for the water intake. The potential earthfill dam failure is an important issue that must considered during the reservoir filling and during its operation. Factors such as potential internal erosion and piping caused by seepage can lead to dam failure or disaster. The initial slope stability analysis of earth dams design must-be carried out such that the risk of embankment failures can be minimized.

In collaboration with KeTTHA (Ministry of Energy, Green Technology and Water Malaysia) a technical visit to the Kelau Dam in Pahang has been carried out on 2/02/2012, lead by Dr Mohd Ashraf Mohamad Ismail, in order to gain an in depth knowledge on the design and construction of the earth fill dam. The study commenced with collection of geological and geotechnical information for the area (Figure 1). Detailed site investigation revealed that the bedrock around the dam site is comprised of alternating beds of carbonaceous shales and siltstones, with phyllites being the most common representative mineral/rock. The physical properties of the soil change with the degree of weathering and the soil material ranges from stiff clay to silt with varying amounts of sand and gravel. The soil zone has low permeability and the rock zone which will served as the dam foundation is quite impervious due to the joints being tight and infilled with clayey matrix.

Foundation grouting is one of important elements of an earth fill dam in order to lengthen the underlying seepage path and to seal up cracks and voids so that the permeability of the foundation can be minimized (Figure 2). Therefore, core samplings with check holes boring (Figure 3) and phenolphthalein indicator (Figure 4) were carried out to ensure the foundation was grouted to the intended Lugeon value (Lu).

Figure 1: View on the embankment towards the upstream surface

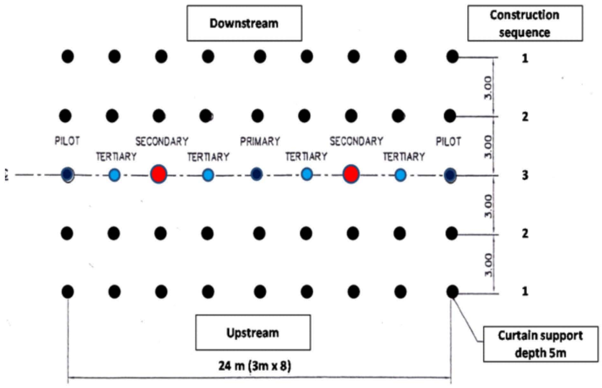

Figure 2: Plan view of the curtain grouting hole arrangement

Figure 3: Core sampling with check hole boring for curtain grouting

Figure 4: Phenolphthalein as indicator for foundation groutability

A conceptual model of the dam, shown in Figure 5, was developed after the site visit and data collection stage. An evaluation of the dam stability were carried out under four main critical conditions namely end of construction, steady state, steady state with seismic loading and rapid drawdown. The dam slope stability analyses were carried out using limit equilibrium method (LEM) and shear strength reduction method together with seepage analysis using finite element method (FEM). It was found that the rapid drawdown and steady states with seismic loading conditions were more critical as compared to the steady state and end of construction conditions (Figure 6-9). The 2-D conceptual model of the earth-fill dam can therefore be classified as stable under all critical loadings as the strength reduction factor (SRF) and factor of safety (FoS) were more than the minimum FoS required. Table 1 summarizes the results of the stability analyses under all critical loading conditions computed by both LEM and FEM. It can be observed that the FOS computed by LEM and FEM were close to each other where differences in percentage were less than 6 %. Based on the seepage qualitative and quantitative results analyses, piping failure at the toe of downstream slope was unlikely to occur due to systematic arrangement of filters and drains at internal surfaces of slope.

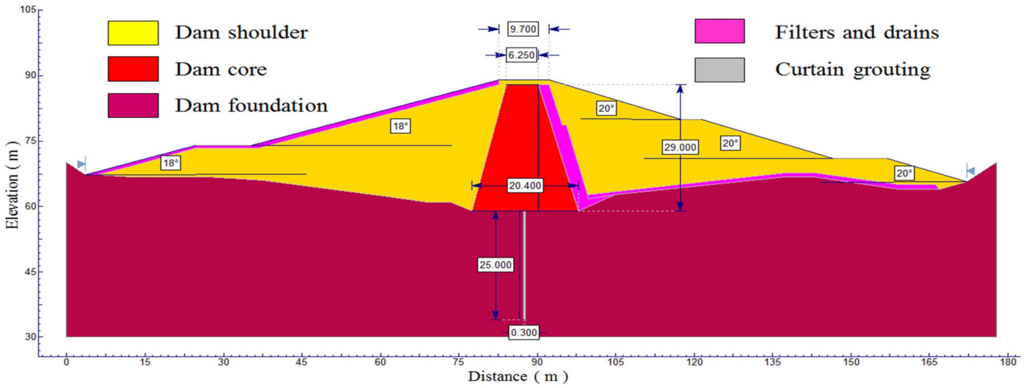

Figure 5: 2D conceptual model for Kelau Dam

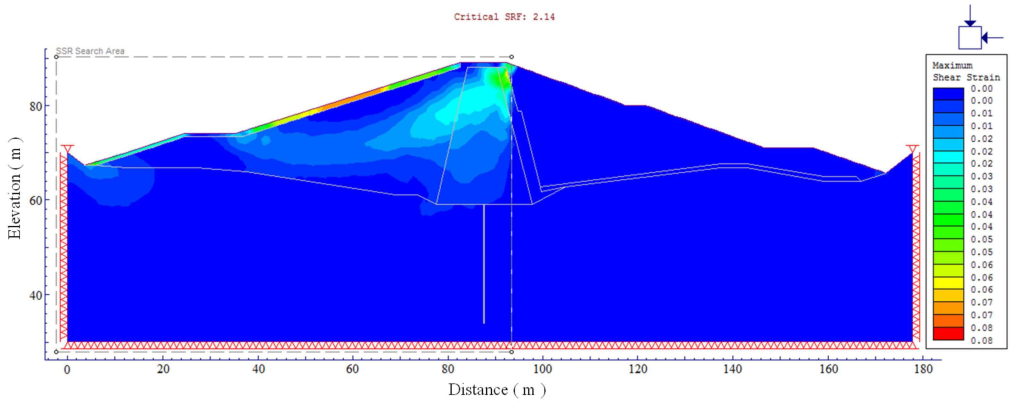

Figure 6: SRF=2.14 for upstream slope during end of construction

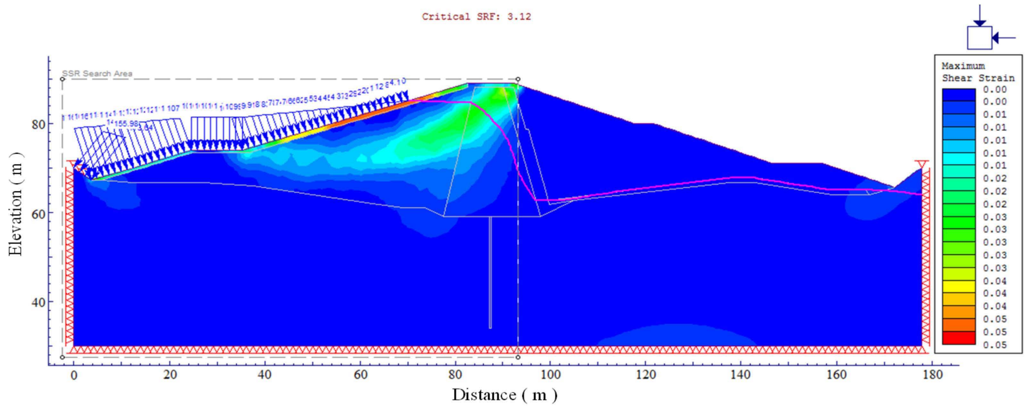

Figure 7: SRF=3.12 for upstream slope during steady state condition

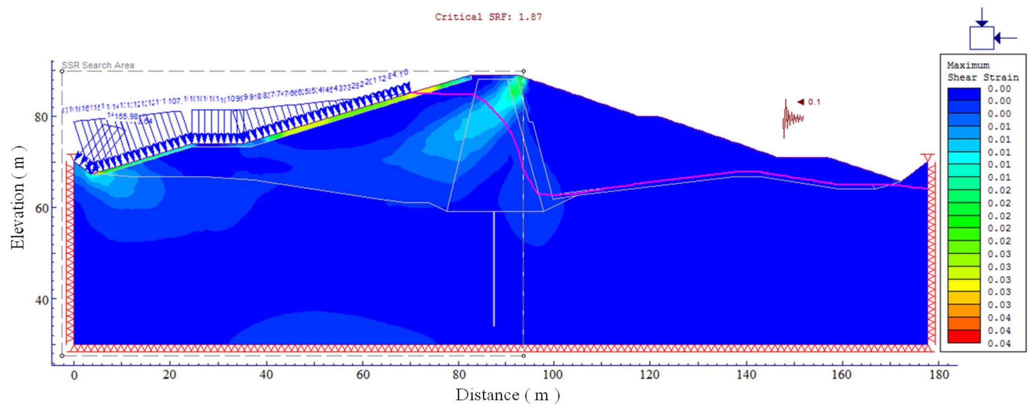

Figure 8: SRF=1.87 for upstream slope during steady state with seismic loading condition

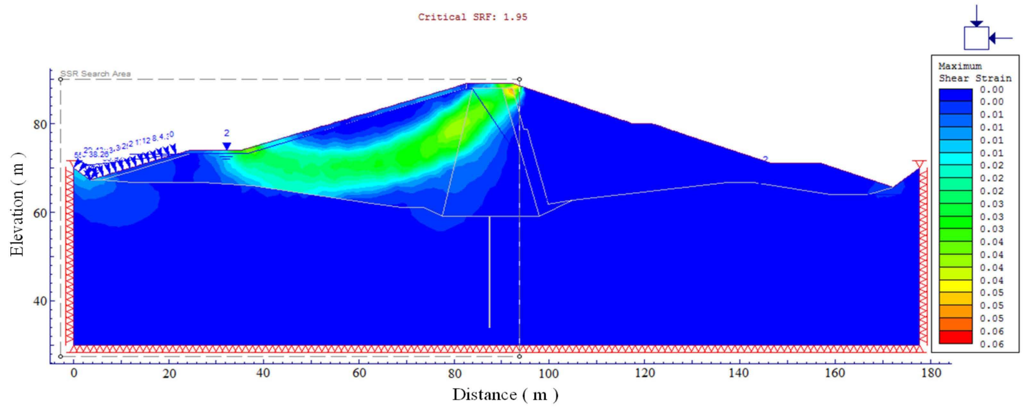

Figure 9: SRF=1.95 for upstream slope during rapid drawdown condition

Table 1 Stability analysis results using LEM and FEM for all critical loading conditions

Loading condition	Minimum FOS (USACE, 2003)	LEM GLE/Morgenstern-Price		FEM		Percentage of difference between LEM and FEM (%)	
		Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
End of construction	1.3	2.068	1.961	2.14	2.01	3.48	2.50
Steady state	1.5	2.948	2.515	3.12	2.61	5.83	3.78
Steady state with seismic loading of 0.1g	1.1	1.872	1.830	1.87	1.89	-0.11	3.28
Rapid drawdown	1.2	1.852	-	1.95	-	5.29	-

Conclusion

From the results obtained, the conceptual model of the earth fill embankment dam can be classified as stable under all critical loadings because the FOS and SRF obtained are more than the minimum requirement.The FOS and SRF computed by LEM and FEM with shear strength reduction technique for the four critical conditions are close to each other where the percentages of difference are all less than 6%. Hence, both methods are satisfactory for engineering usage in the stability analysis of earth-fill dam. The successful operation of the dam under the full range of loadings requires a comprehensive evaluation and monitoring throughout the design and operation period. Therefore, the design parameters will be revised from time to time during the construction phase for a more detailed analysis. Besides, the amount of seepage at the downstream toe will also be measured and compare with the analysis result in order to avoid seepage failure. Finally, the authors gratefully acknowledge the assistance and cooperation given by KeTHHA (Ministry of Energy, Green Technology and Water Malaysia) and Tokyo Electric PowerServices Co., Ltd. (TEPSCO) to carry out this study successfully.

Deflection Behavior of SDSP Model in FEM Analysis for Landslide Prevention

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Slope stabilization using passive piles, with minimum diameter of 300mm, is one of the oldest methods adopted in landslide prevention measures. Mechanism of such measure has been rigorously studied by various researchers (Ito & Matsui 1975; Jeong et al. 2003; Mujah et al. 2012). In recent years, a new type of pile called small diameter (90mm–300mm) steel piles (SDSP) has been developed, aimed to function as both landslide countermeasure and slope reinforcement. Though previous studies clearly explained the prevention mechanism of large diameter passive piles in single row however, this research aims to pave a way into looking at the potential of multiple rows arrangement of SDSP that combines both linear and planar countermeasures and describes their deformation mechanism. To that end, a numerical model using finite element analysis (FEA) PLAXIS 2D code and also an analytical approach were carried out.

1. FEA in PLAXIS 8.2 (2D) and Analytical Approach

Mohr-Coulomb's elastic-perfectly plastic soil model was employed in the study in which the mesh generation of the model was synchronized with the desirable soil relative densities of Dr=30% and Dr=80%. The testing schedule for the analysis as well as both the soil and material properties adopted in the model are shown in Table 1, Table 2 and Table 3 respectively.

Table 1: Testing schedule of the analysis

Type of aluminum bar	Soil's relative density, Dr (%)	Type of reinforcements			
		Unreinforced (Case 1)	3C x 1R (Case 2)	6C x 2R (Case 3)	9C x 3R (Case 4)
Square bar 10 mm x 10 mm □	30	✓	✓	✓	✓
	80	✓	✓	✓	✓
Circular bar 3 mm diameter ○	30	✓	✓	✓	✓
	80	✓	✓	✓	✓

C = No. of column bars, R = No. of rows of the arranged bars

Table 2: Soil properties

Parameter	Name	Sand	Unit
Material model	Model	Mohr-Coulomb	–
Material behavior	Type	Drained	–
Soil behavior above phreatic level	γ_{dry}	16 – 17	kN/m^3
Horizontal permeability	Kx	1.0	m/day
Vertical permeability	Ky	1.0	m/day
Young's modulus	E	30000 – 80000	kPa
Poisson's ratio	ν	0.3	–
Cohesion	C	1.4	kPa
Friction angle	φ	30 – 34	°
Dilatancy angle	ψ	0.4	°
Interface strength ratio	R	0.6 – 1.0	–
Global coarseness	Coarseness	loose – dense	–

Table 3: Material (pile and wall models) properties

Parameter	Name	Pile	Unit
Material model	Model	Plate	–
Material behavior	Type	Elastic	–
Normal stiffness	EA	1.85 x 10^9	kN/m
Flexural rigidity	EI	1.4 x 10^5	kNm^2/m
Equivalent thickness	d	0.03	m
Weight	w	0.35	kN/m/m
Poisson's ratio	ν	0.15	–

In addition, mathematical approach based on the uncoupled analysis of laterally loaded passive piles (Ito & Matsui 1975; Jeong et al. 2003) is adopted for results comparison. Pile deflection w, above and below the displacement interface are calculated based on Equation 1 and Equation 2 respectively.

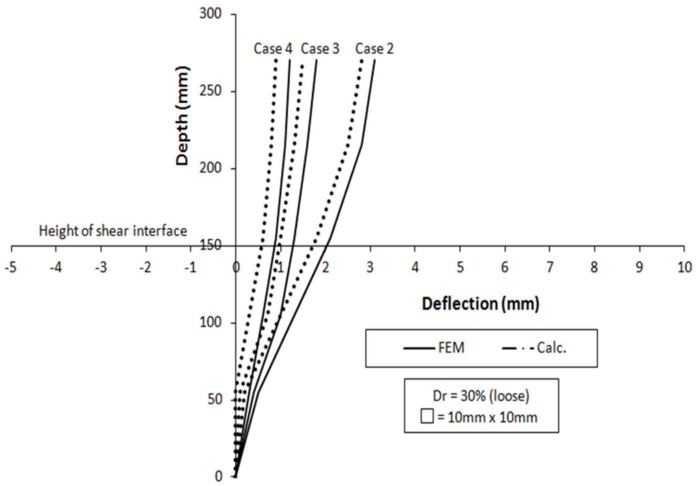
$$EI\left(\frac{d^4 w}{dz^4}\right)_i = p = K_i\left[\left(y_s\right)_i - w_i\right] = K_i\delta_i \tag{1}$$

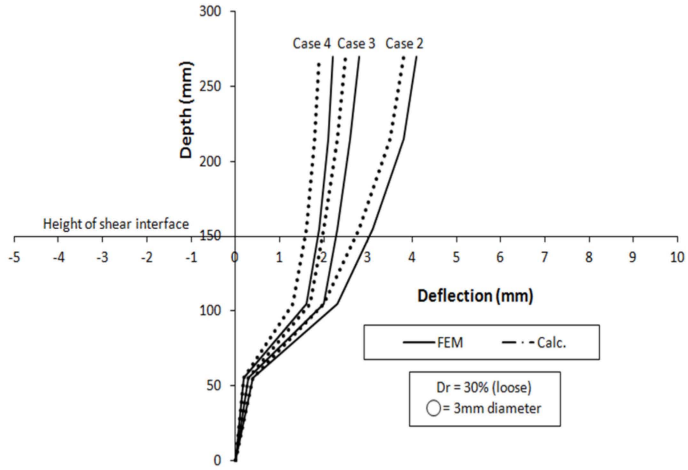
$$EI\left(\frac{d^4 w}{dz^4}\right)_i + K_i w_i = 0 \tag{2}$$

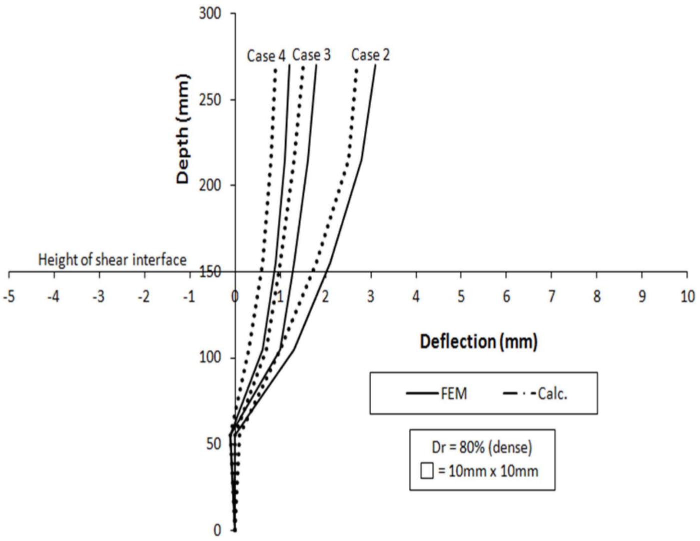
where, w = lateral pile displacement, y_s = free-field soil movement at each depth before pile installation, K_i = elastic constant of soil, EI = flexural rigidity of the pile, δ_i = relative displacement between y_s and w.

2. Relationship between pile deflection and soil vertical depth

Figure 1 portrays the deflection behaviors of SDSP under lateral loading. From the figure, it was observed that the deflection of both circular and square piles in loose ground was observed to be dependent on the EI of the reinforcing material. No apparent correlation between pile shape and ground condition was found in dense ground since all piles were displaced in the range of 0.2mm–3mm due to the confining effect of the densely compacted soil. It was also observed that the changes in ground densities had significantly influenced soil's dilatancy, in this case, Toyoura Sand. The variation of the pile deflection distribution depicted in Figure 2, as a result of dilative and contractive sand behavior, contributes to the lower pile resistance in loose ground condition regardless of the piles arrangement. This also explains the negative normal stress and deflection in loose ground condition especially under the height of shear interface.







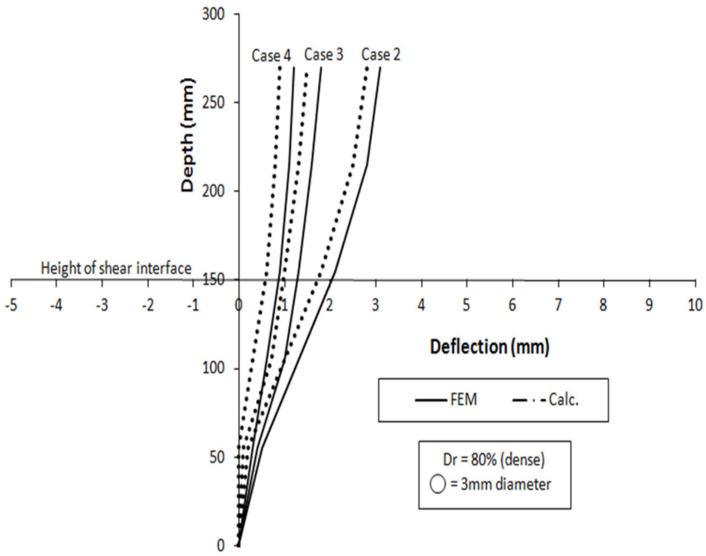


Figure 1: Variation of the pile deflection with vertical soil depth

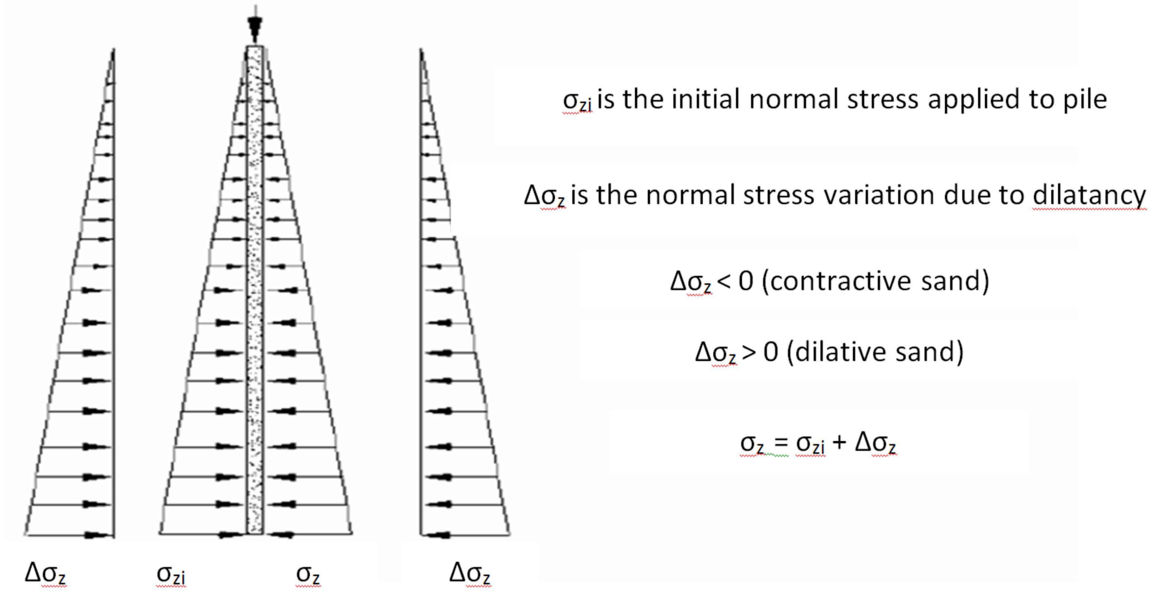


Figure 2: Variation of normal stress distribution

Conclusions

In this study, the deflection characteristics of SDSP was studied in which the effectiveness of the reinforcing effect of SDSP is validated by their long term ability in resisting larger deflection through both the theoretical and analytical analysis. FEM analysis was found to be in good agreement with the calculated results though overestimation was expected due to the assumed 2D plane strain simplification in the presumed conditions for both the circular and rectangular bars in the numerical simulation. Resistance to both lateral and axial forces is significantly enhanced with multirows arrangement of SDSP in landslide prevention.

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