Numerical and Parametric Analysis of Settlement in Unreinforced Embankments on Soft Soils

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ABSTRACT: This paper, the first in a series of three, investigates the settlement behavior of four unreinforced embankments on soft soils through numerical and parametric analysis. The embankments have dimensions of 3.5 meters in height and 17 meters in width and are modeled on a soft soil layer that extends 30 meters horizontally, with thicknesses ranging from 5 to 20 meters. The soil was modeled using two different plasticity criteria: the Modified Cam Clay criterion for the soft soil and the Mohr-Coulomb criterion for the embankment material. A total of forty numerical simulations were conducted to analyze the influence of various geometries and soil properties. The results present and discuss the impact of soil thickness, over-consolidation ratio (OCR), recompression index (k), and critical state slope (M) on settlement and vertical volume of mobilized soil. Normalized plots allow settlement comparisons over time and horizontal position, identifying OCR and κ as the most influential parameters.

KEYWORDS: Soft Soil, Embankments, Numerical Analysis, Parametric Analysis, Abaqus, Settlement.

1 INTRODUCTION

The expansion of urban areas, the demand for improved services and communications, the development of industry, land reclamation in overpopulated areas, and the development of infrastructure on soft soils require a comprehensive understanding of behavior of embankments on soft soils. Construction and design techniques and monitoring methods are used to ensure stability, calculate the rate and magnitude of deformation, and analyze the performance of embankments during and after construction. The stability, deformability, and performance aspects of embankments on soft soils have been extensively investigated in numerous studies (Brugger 1996, Ryde 1997, Almeida and Marques 2014, Massad 2010, among others).

Settlement, lateral displacement, and pore pressure analysis are emphasized to prevent structural collapse (Ryde 1997, Brugger 1996). Methods for predicting the behavior of embankments on soft soils are based on stability analysis during and after construction and on the evolution of settlement, horizontal displacement, and pore pressure over time (Ryde, 1997; Brugger, 1997; Massad, 2010). Settlement analysis is very important even in situations where immediate failure is unlikely, because it can eventually lead to the collapse of a structure, even if the factor of safety against shear failure is high (Lambe and Whitman, 1969).

In geotechnical engineering, surface settlement plates, deep settlement gauges (strainmeters), and profilometers are commonly utilized for the measurement of total surface settlement (ρ), settlement at specific depths, and settlement profiles along horizontal lines, respectively. Theoretical estimation of settlement has traditionally been based on One-Dimensional Consolidation Theory, initially formulated by Terzaghi (1925) and further elaborated by Terzaghi and Fröhlich (1936). This theory posits a linear, one-dimensional consolidation process and assumes linear stress-strain relationships. It elucidates consolidation as the gradual reduction in the volume of a saturated soil over time due to the expulsion of water from voids, induced by the self-weight of the soil or external loads (DNIT 381, 2022). However, estimating the parameters necessary for settlement computation based on One-Dimensional Consolidation Theory often entails significant uncertainty. Recognizing this challenge, Asaoka (1978) proposes an alternative settlement prediction approach based on the "Observational Procedure”. Concurrently, Finite Element Methods (FEM) are increasingly used in evaluating the stability, deformability, and performance of embankments on soft soils, particularly in scenarios involving complex structures or parametric studies (Ryde, 1977).

In an effort to better understand the performance of embankments in soft soils, numerical and parametric analyses were performed using Abaqus. Four unreinforced embankments with different soft soil thicknesses were studied. The effects of changes in the parameters M, k and OCR on settlement and vertical volumes of mobilized soil below the embankment and beyond the toe of the slope were investigated and discussed.

2 METHOD

2.1 Models Description

The numerical analysis of four unreinforced embankments on soft soils was performed using Abaqus software and assuming the plane strain condition. The 2D models consisted of a 3.5 m deep and 17 m long embankment of granular material with a slope of 1:2 (vertical to horizontal) over a soft clay layer 30 m long and 5 to 20 m thick. Due to the symmetry of the model, only half of the domain was simulated, as shown in Figure 1, where H_s represents the thickness of the soft soil layer.

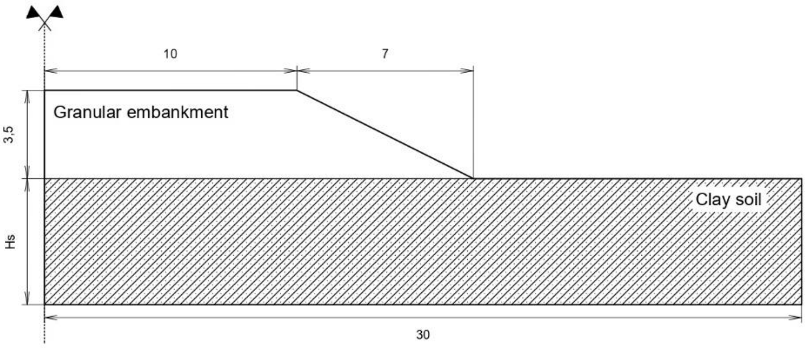


Figure 1. Half-domain of the numerical model of the embankment on the soft soil, in m.

2.2 Geotechnical Parameters

The soft clay was modeled as a homogeneous solid with elastoplastic behavior using the Modified Cam Clay plasticity criterion. Conversely, the granular material was simulated in a dry state as a homogeneous solid body using the Mohr-Coulomb criterion. The geotechnical parameters for both the granular material and the clay soil are given in Table 1, where the clay parameters are typical of certain regions in Florianópolis, Brazil, as presented by Oliveira, 2006 and Baran, 2014.

Table 1. Geotechnical parameters of the soft soil and granular material.

Granular material of the embankment		Clay soil	
Parameter	Value	Parameter	Value
Initial void ratio - e_0	0.65	Initial void ratio - e_0	2.5
Bulk unit weight - γ (kN/m³)	20	Bulk unit weight - γ (kN/m³)	15
Cohesion - c (kN/m²)	2	Recompression index - κ	0.065
Internal friccional angle - ϕ (º)	30	Poisson's ratio - ν	0.33
Dilatancy angle - ψ (º)	0	Compression index - λ	0.65
Elastic Module - E (kN/m²)	1000	Slope of the critical state line - M	1
Poisson's ratio - ν	0.3	Overconsolidation ratio - OCR	0.75, 1.0, 1.5, 3.0
Permeability coefficient - k (m/s)	0.01	Size of the yield surface in the wet side - β	1
		Ratio of the flow stress - K	1
		Permeability coefficient - k (m/s)	2.50E-08
		Lateral earth pressure at rest – $K_0 = 1 - \text{sen}\,\phi$	0.57

2.3 Simulation Sequences

The numerical simulations consisted of three stages, reflecting the sequential construction process of the single-phase embankments. The first stage involved the application of the Body Force option to stablish the initial geostatic stresses within the soft soil. The second stage then involved the gradual construction of the embankment to a height of 3.5 meters over a period of one month. Finally, the third phase involved monitoring the embankment's performance, including measuring vertical and horizontal displacements and excess pore water pressure, over a period of 48 months (4 years).

2.4 Boundary Conditions and Mesh Discretization

Physical and drainage boundary conditions were set to accurately simulate real embankment conditions under plane strain. For the physical boundary conditions, horizontal (U1=0) and vertical (U2=0) displacements were fixed at the bottom, while horizontal displacement (U1=0) was constrained at the right and left sides. Throughout the simulation, the soft soil surface maintained a zero-pore pressure (U8=0) as part of the drainage boundary conditions.

Figure 2 illustrates the physical boundary conditions and mesh configuration of the numerical model with a 5 m thick layer of soft soil. The mesh has been refined particularly in areas where significant stresses and strains are expected.

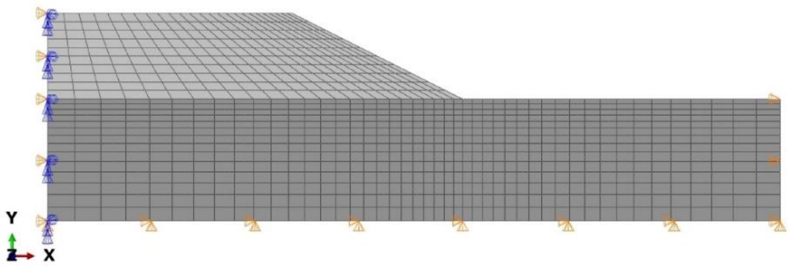


Figure 2. Boundary conditions and mesh discretization.

The numerical model used finite elements of type CPE8R (a quadrilateral flat deformation element with 8 nodes, bi-quadratic displacement, and reduced integration) for the embankment domain, and CPE8RP (a quadrilateral flat deformation element with 8 nodes, bi-quadratic displacement, bilinear pore pressure, and reduced integration) for the foundation domain.

2.6 Parametric Analysis

To investigate the effect of soil parameter variation on embankment performance, 40 analyses were performed, with 10 analyses for each numerical model. The parameters varied included the slope of the critical state line (M), the recompression index (κ), the overconsolidation ratio (OCR), and the soft soil thickness (H_s). Table 2 shows the parameters varied for each analysis and their respective values. Analysis 1 used parameters set to reference values, while subsequent analyses varied individual parameter values while holding others constant. With the exception of the OCR of 0.75, the remaining values used in the parametric analysis are in the range of the typical values for Florianópolis Clay (see Oliveira, 2006; Baran, 2014). The OCR of 0.75 was used only to analyze the behavior of a clay under consolidation, not for practical purposes.

Table 2. Parametric analysis.

Analysis	M	Analysis	κ	Analysis	OCR
Analysis 1 (reference)	**1.0**	**Analysis 1**	**0.065**	**Analysis 1**	**1.00**
Analysis 2	1.1	Analysis 5	0.050	Analysis 8	0.75
Analysis 3	1.2	Analysis 6	0.080	Analysis 9	1.50
Analysis 4	1.3	Analysis 7	0.095	Analysis 10	3.00

The displacement results were evaluated over time and width. Figure 3 shows 3 designated points (B, E, and H) at the soil surface along with the horizontal line LH2 where data extraction from Abaqus to Excel was performed. Point data analysis was performed over time and horizontal line data analysis was performed over width.

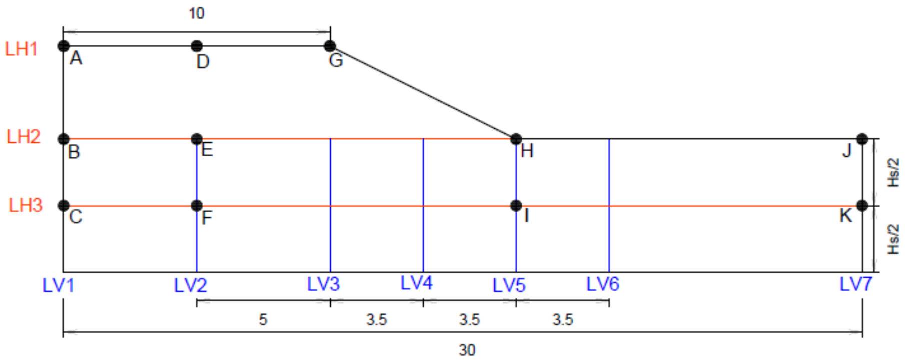


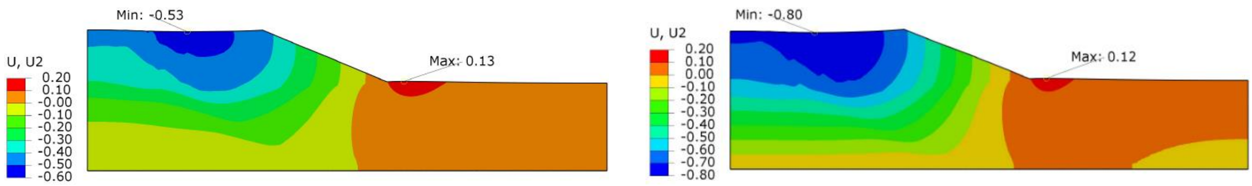
Figure 3. Points and lines of interest for data extraction, in m.

3 RESULTS AND DISCUSSION

The settlement magnitudes are influenced by the properties and thickness of the soft soil layer and of the embankment, while the settlement time depends primarily on the properties and thickness of the soft soil. This section focuses on the analysis of settlement patterns and soil volumes mobilized during and after embankment construction. Stability analyses based on the relationship between settlement and horizontal displacement and between vertical and horizontal volumes are discussed in a separate paper.

Figure 4 depicts the spatial distribution of settlements at two time periods: 1 month (end of embankment construction) and 48 months. The blue areas represent higher settlement, while negative values indicate downward displacement. In both periods, the soil beneath the embankment experiences downward movement, while the soil near the toe of the embankment undergoes upward movement.

Due to space limitations, only selected typical figures are presented. However, the discussions cover the behavior observed in all 40 analyses performed.



(a) 1 month. (b) 48 months.

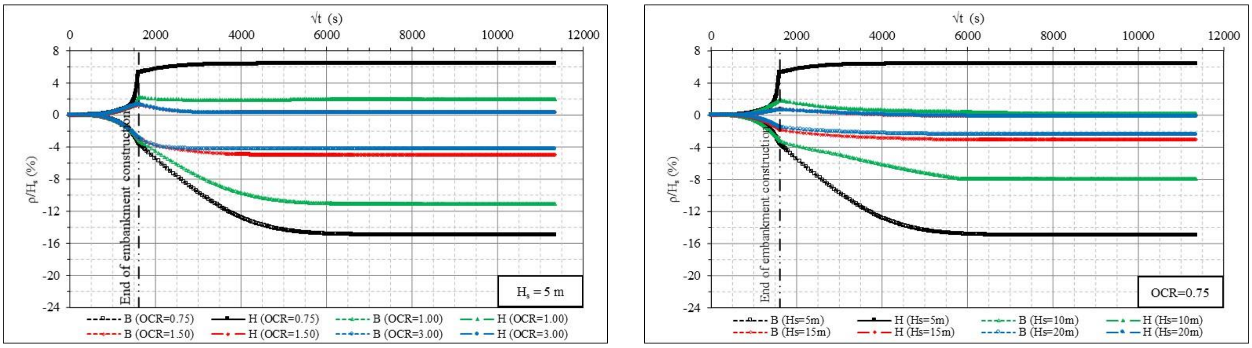
Figure 4. Spatial distribution of settlement.

Figure 5 illustrates the variation of the normalized settlement (ρ/H_s) measured at points B and H over $\sqrt{t}$. Figure 5a demonstrates the influence of the OCR parameter on the magnitude of ρ/H_s for models with H_s of 5 m, while Figure 5b illustrates the influence of the soft soil thickness on the magnitude of ρ/H_s for analyses with OCR=0.75.

In all analyses, the settlement at point B increases nonlinearly over time until the end of consolidation and then remains constant, as expected. Conversely, the vertical movement at point H initially increases (upward) during embankment construction and subsequently decreases to zero before the end of consolidation, except in analyses with H_s of 5m and OCR of 0.75 and 1. The reversal of vertical movement at point H may be attributed to the consolidation process or numerical modeling issues, requiring further investigation to explain this behavior.

An increase in H_s leads to a reduction in settlement stabilization time (T_{set}). However, the T_{set} is less than 9.5 months. For $H_s \geq 10$ m, T_{set} does not vary significatly in analyses with $M > 1$, $\kappa > 0.065$, and $OCR > 1$. Analyses with $H_s = 5$ m show that variations in M and κ have no significant influence on T_{set}. However, T_{set} decreases as OCR values increase from 0.75 to 3.

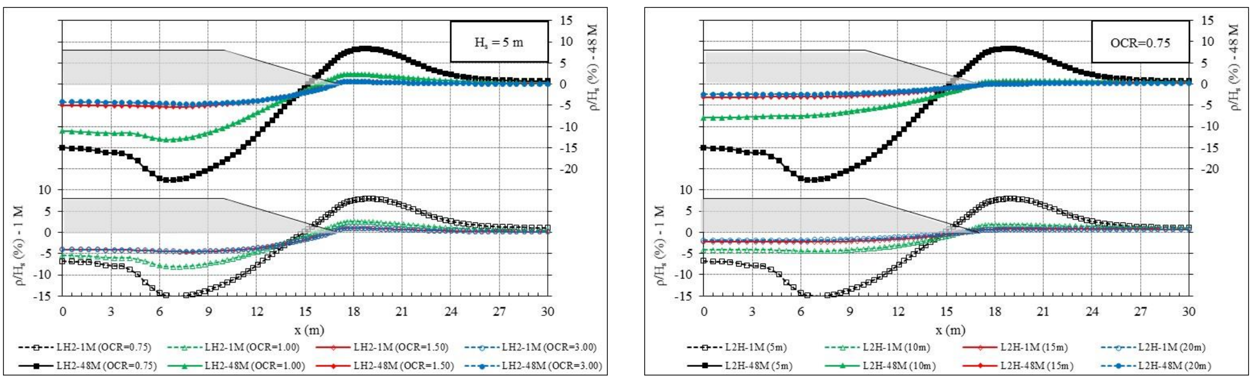
Regardless of H_s value, increasing parameter κ reduces ρ/H_s. The maximum ρ/H_s tends to occur not at the symmetry axis, but in crest slightly before the start of the embankment slope for $H_s \geq 10$ m. At the symmetry axis, ρ/H_s varies between 1.91% and 3.56% for H_s of 20 m, between 2.25% and 4.22% for H_s of 15 m, between 4.39% and 7.99% for H_s of 10 m, and between 4.22% and 15.00% for H_s of 5 m. In other words, ρ/H_s decreases with the increasing H_s.



(a) (b)

Figure 5. Variação de ρ/H_sversus ($\sqrt{t}$)

Figures 6 and 7 show the normalized settlement variation along the L2H line at the soil surface. Figure 6 normalizes the settlement by the thickness of the soft soil, while Figure 7 considers the mean geostatic stress (σ'_{v0}) and the embankment surcharge ($q = \gamma H_e = 70$kPa). In both figures, significant settlements are observed mainly below the crest of the embankment. The ongoing consolidation process induces soil uplift near the toe of the slope, with a subsequent significant reduction in these effects upon completion of embankment construction.



(a) (b)

Figure 6. Variation of ρ/H_s along L2H line.

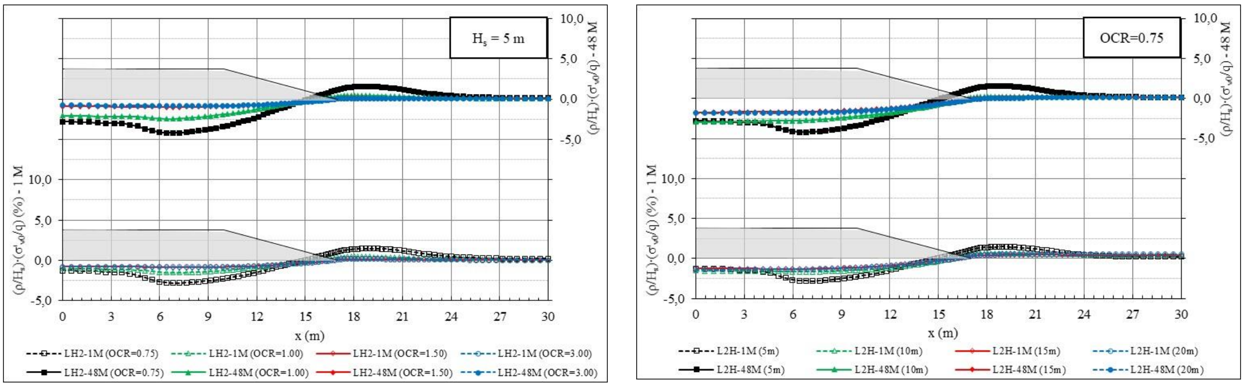
An increase in H_s generally results in a decrease in the ρ/H_s for a given set of soil properties. Table 3 provides a summary of the percentage range of ρ/H_s measured at the center of the soil surface at 1 month and

48 months. The effect of variations in the M and OCR parameters on ρ/H_s is minimal, especially for $H_s \geq 10$ m and $OCR \geq 1$. However, contrasting behavior was observed in analyses with $H_s = 5$ m and variations in the κ parameter.

Table 3. Percentage range of ρ/H_s for analyses with different H_s.

Parametric analysis	Percentage of ρ/H_s - (1 month) | (48 months)			
	$H_s = 5$ m	$H_s = 10$ m	$H_s = 15$ m	$H_s = 20$ m
M	(5.0-5.1) | (10-10.8) |	(4.1) | (5.5)	(2.3) | (2.9)	(1.9) | (2.5)
k	(4.7-6.6) | (10.2-12.8)	(3.3-5.5) | (4.4-8.0)	(1.8-3.1) | (2.3-4.2)	(1.5-2.6) | (1.9-3.6)
OCR	(4.1-6.8) | (4.2-15.0)	(4.1) | (5.5-7.9)	(2.3) | (2.9)	(1.9) | (2.5)

The settlement results, normalized as $(\rho/H_s)\cdot(\sigma'_{v0}/q)$, are minimally affected by Hs due to the consideration of the mean effective geostatic stress in each analysis. Increasing κ slightly decreases $(\rho/H_s)\cdot(\sigma'_{v0}/q)$for $H_s \geq 10$ m. The influence of M and OCR on $(\rho/H_s)\cdot(\sigma'_{v0}/q)$ is noticeable only for analyses with $H_s = 5$ m.



(a) (b)

Figure 7. Variation of $(\rho/H_s)\cdot(\sigma'_{v0}/q)$ along L2H line.

Figure 8 illustrates the effect of the parameters κ, M and OCR on the vertical volume of soil mobilized below the embankment (V_{v1}) and on the ratio between the vertical volumes below (V_{v1}) and near the toe of (V_{v2}) the embankment. These volumes were calculated based on an embankment length of 1 m. The variation of parameters M and OCR does not affect V_{v1} and the ratio V_{v2}/V_{v1} in analyses with $H_s \geq 10$ m. Conversely, V_{v1} increases with increasing value of κ. The ratio V_{v2}/V_{v1} is not affected by the variation of κ at the end of the consolidation period, but it is slightly affected by κ at the end of the embankment construction. The range of V_{v1} and V_{v1}/V_{v2} at 1 month and 48 months for different H_s is summarized in Table 4.

Table 4. The range of V_{v1} and V_{v1}/V_{v2} for analyses with different H_s.

Parametric analysis	Range of V_{v1}							
	$H_s = 5$ m		$H_s = 10$ m		$H_s = 15$ m		$H_s = 20$ m	
	1M	48M	1M	48M	1M	48M	1M	48M
M	3.8-5.2	6.3-8.9	8.9	8.8-8.9	7.8	7.1	9.0	7.9
k	4.4-6.5	7.1-9.4	6.9-12.7	6.9-12.7	6.0-11.1	5.5-10.3	7.0-12.9	6.1-11.4
OCR	3.3-8.7	3.3-13.0	8.8-9.0	8.8-11.3	7.8	7.1-7.3	9.0	7.9

Parametric analysis	Range of V_{v1}/V_{v2}							
	$H_s = 5$ m		$H_s = 10$ m		$H_s = 15$ m		$H_s = 20$ m	
	1M	48M	1M	48M	1M	48M	1M	48M
M	0.11-0.18	0.04-0.10	0.21	0.06	0.20	0.06	0.21	0.04
k	0.17-0.20	0.09-0.10	0.19-0.30	0.06	0.19-0.22	0.06	0.20-0.22	0.04
OCR	0.05-0.21	0.10-0.33	0.21	0.06-0.07	0.20	0.06	0.21	0.04

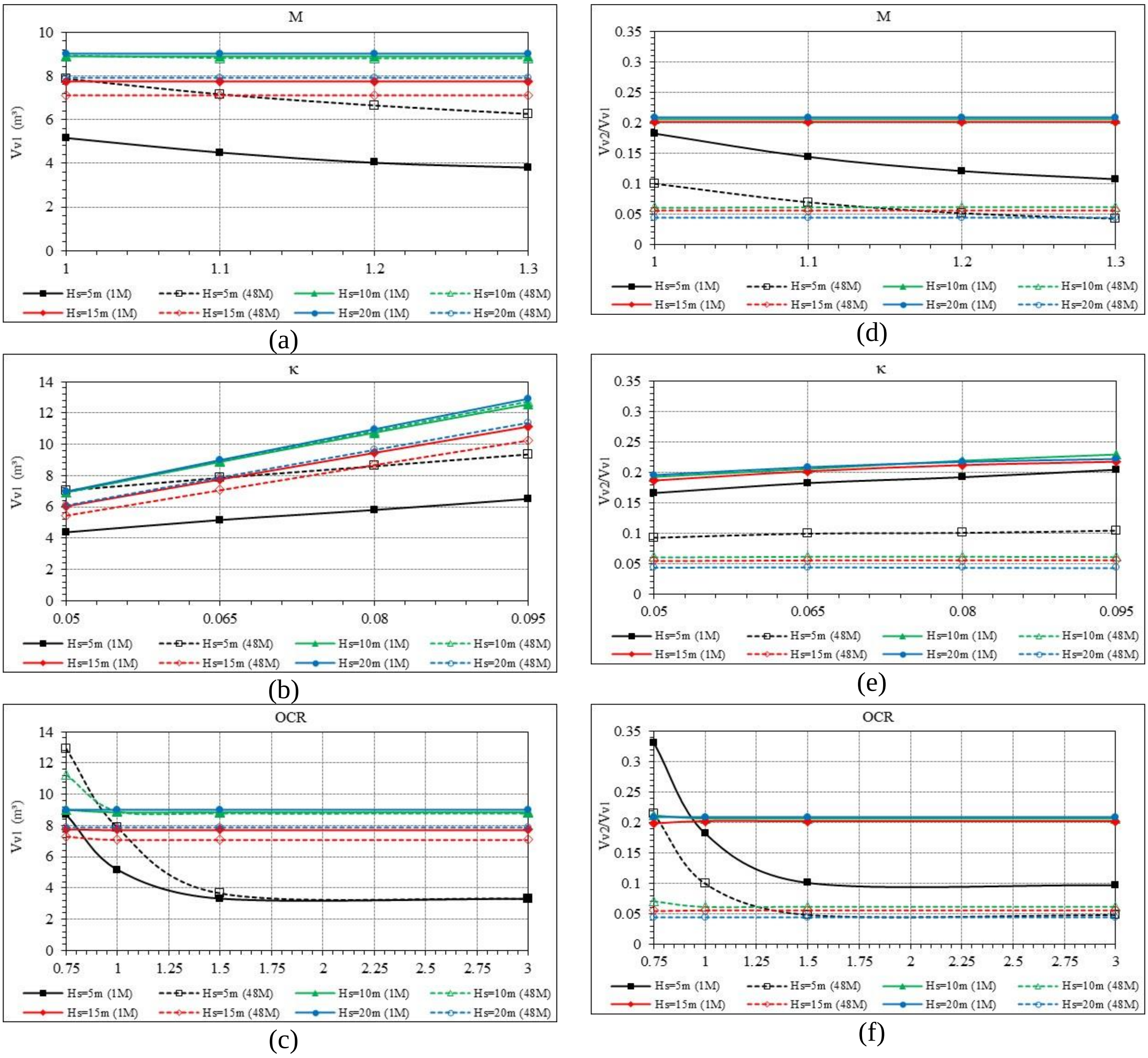


Figure 8. Influence of the parameters κ, M and OCR on V_{v1} and V_{v2}/V_{v1}.

4 CONCLUSIONS

This paper presents the results of 40 numerical simulations that investigate the effects of the variation in parameters M, OCR, κ, and H_s on the settlement and vertical volume of the mobilized soft soil. The key conclusions are presented below:

- the vertical movement (ρ/H_s) near the toe of slope (point H) initially increases (upward) during embankment construction and subsequently decreases to zero before the end of consolidation, except in analyses with H_s of 5 m and OCR of 0.75 and 1. This reversal of vertical movement at point H may be attributed to the consolidation process or numerical modeling issues, requiring further investigation to explain this behavior;
- the effect of variations in M and OCR parameters on ρ/H_s is minimal, especially for $H_s \geq 10$ m and $OCR \geq 1$. However, contrasting behavior was observed in analyses with $H_s = 5$ m and variations in the κ parameter. Regardless of H_s value, increasing parameter κ reduces ρ/H_s.
- an increase in H_s generally results in a decrease in the ρ/H_s for a given set of soil properties.

- an increase in H_s leads to a reduction in settlement stabilization time (T_{set}). However, the T_{set} is less than 9.5 months. For $H_s \geq 10$ m, T_{set} does not vary significatly in analyses with $M > 1$, $\kappa > 0.065$, and $OCR > 1$. Analyses with $H_s = 5$ m show that variations in M and κ have no significant influence on T_{set}. However, T_{set} decreases as OCR values increase from 0.75 to 3.
- $(\rho/H_s) \cdot (\sigma'_{v0}/q)$, are minimally affected by H_s. Increasing κ slightly decreases $(\rho/H_s) \cdot (\sigma'_{v0}/q)$ for $H_s \geq 10$ m. The influence of M and OCR on $(\rho/H_s) \cdot (\sigma'_{v0}/q)$ is noticeable only for analyses with $H_s = 5$ m.
- The variation in parameters M and OCR does not affect V_{v1} and the ratio V_{v2}/V_{v1} in analyses with $H_s \geq 10$ m. Conversely, V_{v1} increases with increasing the value of κ.
- The ratio V_{v2}/V_{v1} is not affected by the variation of κ at the end of the consolidation period, but it is slightly affected by κ at the end of the embankment construction.
- the quality of the analysis underscores the effectiveness of Abaqus software in assessing the performance of geotechnical structures that require monitoring of excess pore pressure.

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