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Numerical Investigation of Consolidation Settlement for Runway Construction on Soft Soil: A Case Study in Sumbawa, Indonesia

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Abstract. Runway construction on soft soil presents significant engineering challenges due to excessive settlement, which can affect structural stability and long-term performance of transportation infrastructure. This study investigates the settlement of a runway in Sumbawa, Indonesia using the Finite Element Method (FEM) in Plaxis 2D. The Hardening Soil Model was applied to realistically capture nonlinear soil behavior. Input parameters were derived from a series of N-SPT data and laboratory test results. The findings indicate that during the operational phase, the maximum and minimum settlement were 307.1 mm and 2.491×10^{-3} mm, respectively. Meanwhile, consolidation-induced settlement reached a maximum of 357.97 mm and a minimum of 10.6 mm. The distribution of total settlement along the runway varied depending on soil characteristics. Sections with predominantly clayey soil exhibited greater settlement, whereas areas with sandy soil experienced significantly lower settlement.

Keywords: Finite Element Method (FEM), Numerical Modeling, Runway, Soft Soil, Transportation

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1. Introduction

Constructing on soft soil presents considerable engineering challenges due to its inherent characteristics, such as low shear strength, high compressibility, large void ratios, and a high potential for excessive settlement [1], [2]. These properties necessitate careful consideration during the analysis and design phases to ensure the stability of structures built on soft soil. The distribution of soft soils in Indonesia is generally found in coastal plains, including: the East Coast of Sumatra, the North Coast of Java, the West – South Coast of Kalimantan Island and the South Coast of Papua Island. The area itself is estimated to be around 20 million hectares or about 10 percent of Indonesia's total land area [3]. Moreover, Several studies have research the characteristics of soil in Indonesia [1], [2], [4], [5]. Various techniques are commonly employed to enhance soil strength and mitigate settlement issues. However, predicting and managing settlement behavior remains a critical aspect of the design and construction process.

In particular, airport infrastructures such as runway, taxiway, and apron, demand stringent control over settlement due to strict operational tolerances. When a structure is built on soft soil, the applied load induces three primary types of settlement: immediate settlement, consolidation settlement, and secondary settlement [6]. Among these, consolidation settlement plays a dominant role, as it primarily results from volume changes due to the gradual drainage of water from the soil matrix during the consolidation process [7]. Consequently, settlement in soft soil occurs mainly due to consolidation, which is influenced by factors such as the loading ratio, consolidation pressure, and load duration [8]. If not accurately predicted and controlled, excessive settlement can result in structural instability, uneven surfaces, and increased maintenance costs. Therefore, a precise estimation of consolidation settlement is crucial to ensure the long-term stability and functionality of the constructed runway.

Accurate prediction of settlement on soft soil is a fundamental challenge in geotechnical engineering due to the soil's complex behavior under load and its highly site-specific characteristics. Over the years, several approaches have been developed to address this challenge, including theoretical approaches [9]–[12], machine learning (ML) models [13], field instrumentation and monitoring [14], and numerical methods such as Finite Element Method (FEM). However, empirical and theoretical methods, although useful for preliminary assessments, often rely on simplified assumptions and may not account for site-specific variability [15]–[17]. Field monitoring provides accurate results but are often limited by high costs and extended data collection periods [18]. Meanwhile, ML models have shown growing potential in geotechnical field; however model often required large and diverse datasets to achieve good performance [19].

Among these methods, FEM has emerged as a powerful and widely accepted tool for simulating the settlement behavior of soft soils. FEM is a reliable tool for predicting settlement due to its to incorporate advanced constitutive models and nonlinear soil behavior [20]. Previous studies have demonstrated that FEM-based predictions closely align with field measurements [21], [22]. Consequently, FEM has been widely used in various geotechnical applications, including the analysis of settlement in Due to its effectiveness, FEM has been extensively used for settlement analysis in runway construction [21], [23], [24], dam [25], and embankments [26]–[30]. A study by Chai et. al., emphasized that the accuracy of FEM in settlement prediction largely depends on the quality of input parameters derived from field and laboratory tests, as well as the selection of an appropriate constitutive model that accurately represents the strength and deformation characteristics of the subsoil [31], [32].

In this study, numerical analysis of settlement due to consolidation for runway construction on soft soil is presented. Field and laboratory data were collected to support the analysis. Plaxis 2D was utilized to predict settlement along the runway, and the distribution map of consolidation was reported to provide insights into the expected ground behavior.

2. Methods

2.1. Project site

The project site for this case study is located at a new private airport in Poto Tano, Sumbawa, Indonesia. The scope of work of the airport encompasses the airside, landside, utilities, and MEP (Mechanical, Electrical, and Plumbing) systems. The airside facilities include a runway, taxiway, and apron, with approximate dimensions of 86 m × 80 m for the apron, 150 m × 15 m for the taxiway, and a runway measuring 1,500 m in length and 30 m in width. The construction of the airside is planned in three phases. The first phase includes the construction of the apron, taxiway (STA 0+010 to STA 0+160), and a section of the runway from STA 20+000 to STA 20+630 (a 630-meter-long segment). The second phase includes a section of the runway from STA 20+630 to STA 21+350 (a 720-meter-long segment). And the third phase includes a section of runway from STA 21+350 to STA 21+500 (a 150-meter-long segment). This study specifically examines the consolidation settlement behavior of the runway construction, focusing on the section between STA 20+000 and STA 21+500.

2.2. Analysis settlement due to consolidation

This study employs a numerical analysis to evaluate consolidation-induced settlement behavior for runway construction on soft soil using the Finite Element Method (FEM). The analysis was conducted using Plaxis 2D, which is widely adopted in geotechnical engineering due to its robust ability to simulate soil behavior under plane strain conditions. While 3D modeling can provide more comprehensive spatial analysis, 2D modeling was considered sufficient and computationally efficient for this study because the geometry and loading conditions along the runway are largely uniform in the longitudinal direction. This approach aligns with previous research that compared 2D and 3D model for predicting settlement, the result showed that 2D models provided satisfactory results while significantly reducing computational demands [33].

2.2.1 Soil Properties

A series of field investigation to characterize soil properties included Standard Penetration Tests (SPT) were conducted along the runway, denoted as ABH, as illustrated in Figure 1. The results of the Standard Penetration Test (SPT) from ABH-1 to ABH-26 can be observed in Figures 2 to 4. The soil composition along the runway varies significantly, as summarized in Tables 1. The soil conditions along the study area vary significantly. From ABH-01 to ABH-15 (STA 20+650 to STA 21+500), the predominant soil type is clay. A transition zone is observed between ABH-16 and ABH-18 (STA 20+480 to STA 20+600), where the upper 4 meters consist of sandy soil with a medium to dense consistency, while the underlying 4 meters comprise clayey soil. Further downstream, from ABH-19 to ABH-26 (STA 20+000 to STA 20+400), sandy soil becomes the dominant type. However, clayey layers are also present at specific locations, particularly at ABH-23, ABH-24, and ABH-26.

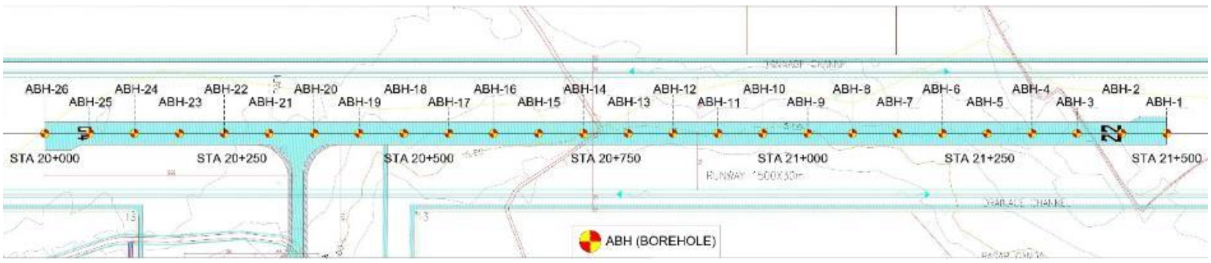

Figure 1. Location of boreholes along the runway

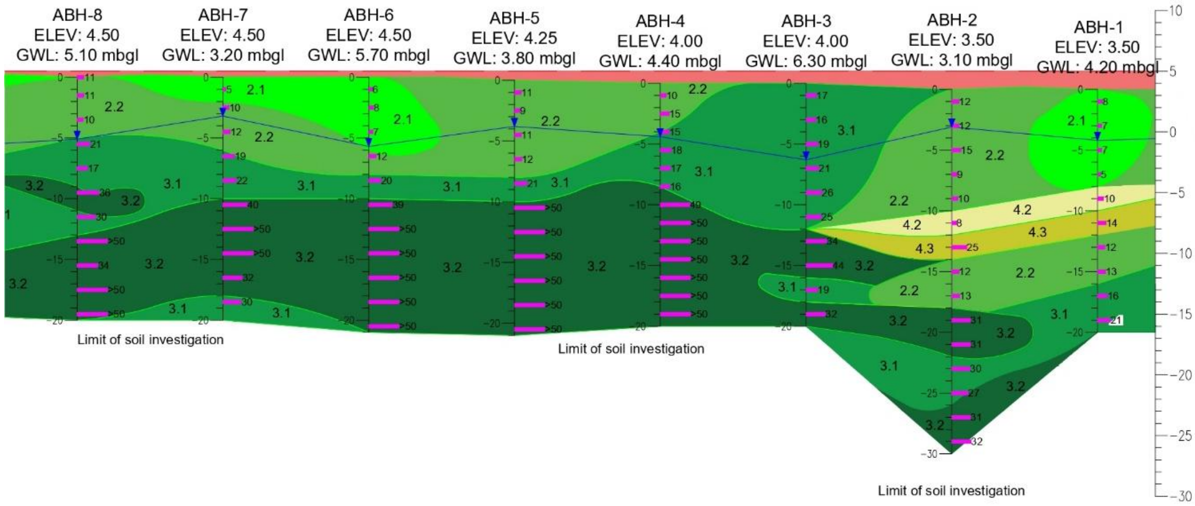

Figure 2. Result of SPT for ABH-1 to ABH-8

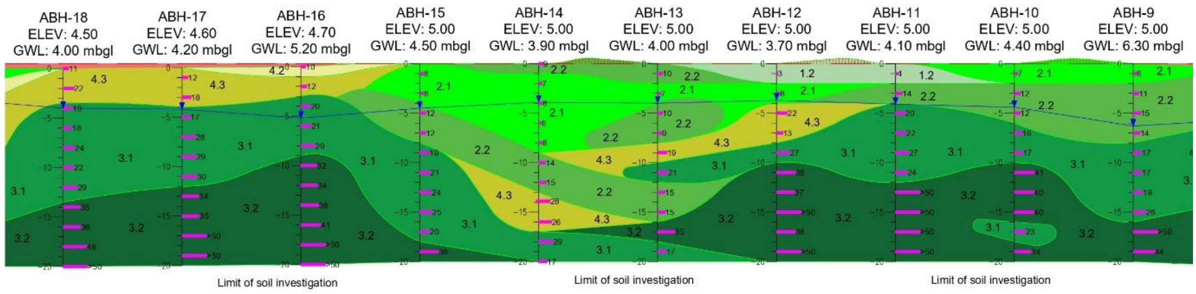

Figure 3. Result of SPT for ABH-9 to ABH-18

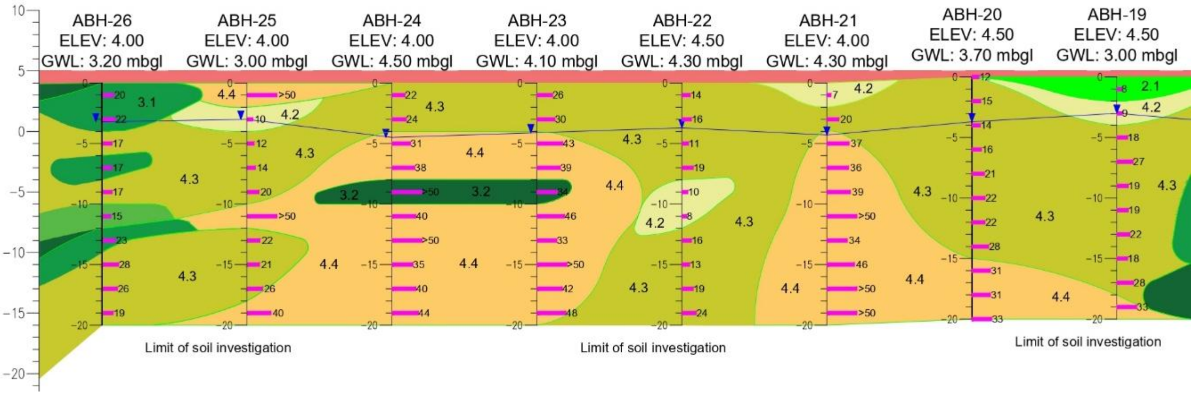

Figure 4. Result of SPT for ABH-1 to ABH-8

2.2.2 Finite Element Modeling with Plaxis 2D

Numerical analysis of runway settlement was carried out using the Finite Element Method (FEM) implemented in Plaxis 2D, utilizing a local axisymmetric model. The Hardening Soil Model (HSM) was employed to simulate the nonlinear, stress-dependent behavior of soft soil. Compared to traditional linear elastic and Mohr-Coulomb models, HSM offers improved accuracy by incorporating stress-dependent stiffness and plastic strain hardening. Key stiffness parameters required for the HSM—namely the secant stiffness in primary loading (E_{50}), oedometer stiffness (E_{oe}^{d}), and unloading/reloading stiffness (E_{ur})— were automatically defines based on the coefficient of consolidation (Cc) obtained from laboratory tests. For boreholes where direct laboratory data were unavailable, these values were estimated using empirical correlations derived from Standard Penetration Test (SPT) N-values,

following the procedures outlined from references [34], [35]. A comprehensive summary of the range of soil parameters used in the Plaxis 2D analysis is presented in Table 1.
The mesh was refined using a fine mesh setting to enhance result accuracy. Then in the initial stage, the model was applied closed flow boundary and closed consolidation boundary. The next step is generating the stage constructions. The construction process analyzed in Plaxis 2D was divided into three stages:

1. Initial Phase: Establishing the initial conditions of the soil profile and its stress distribution.
2. Filling Process: Simulating the filling process over a 14-day period, accounting for the gradual application of the fill load.
3. Active Load and Consolidation: Applying an active load of 15 kPa and observing the subsequent consolidation behavior over time.

This multi-stage approach provided a comprehensive understanding of settlement behavior, highlighting the importance of accurately modeling soil parameters and construction sequences to predict settlement in runway construction projects on soft soil. Settlement observations were made throughout the operational phases and the total settlement due to consolidation.

Table 1. Soil Parameter reference for Plaxis 2D analysis

ABH	Observed Soil Types	γ (kN/m^3)	c' (kN/m^2)	φ' (°)	Ey (kN/m^2)	k (m/day)	cc	e_0
1	Clay, sand	16~17	1~7	23~ 25	4975 ~ 16915	$8.64\text{x}10^{-2}$ ~ $8.64\ \text{x}10^{-5}$	0.626	1.335
2	Clay, sand	15~17	1~7	25~ 28	8955 ~ 30303	$8.64\ \text{x}10^{-2}$ ~ $8.64\ \text{x}10^{-6}$	0,653	1.838
3	Clay	15~17	7	28~ 32	15920 ~ 39801	$8.64\ \text{x}10^{-2}$ ~ $8.64\ \text{x}10^{-7}$	-	-
4	Clay	17	7	25~ 32	9950 ~ 49751	$8.64\ \text{x}10^{-5}$	0.904	1.443
5	Clay	17	5~7	25~ 32	8955 ~ 49751	$8.64\ \text{x}10^{-5}$	-	-
6	Clay	17	5~7	23~ 32	5970 ~ 49751	$8.64\ \text{x}10^{-5}$	-	-
7	Clay	17	5~7	23~ 32	4975 ~ 39801	$8.64\ \text{x}10^{-5}$	0.375	1.064
8	Clay	17	7	25~32	9950 ~ 49751	$8.64\ \text{x}10^{-5}$	0.512	1.587
9	Clay	17	5~7	25~32	7960 ~ 44776	$8.64\ \text{x}10^{-5}$	0.272	0.823
10	Clay	17	5~7	25~32	6965 ~ 39801	$8.64\ \text{x}10^{-5}$	0.759	2.26
11	Clay	17	5~7	22~32	3980 ~ 49751	-	0.72	2.01
12	Clay	17	1~7	22~32	2985 ~ 36816	$8.64\ \text{x}10^{-2}$ ~ $8.64\ \text{x}10^{-5}$	0.55	1.9
13	Clay	17	1~7	25~28	6965 ~ 29851	$8.64\ \text{x}10^{-2}$ ~ $8.64\ \text{x}10^{-6}$	-	-
14	Clay, sand	17	1~7	23~28	5970 ~ 39394	$8.64\ \text{x}10^{-2}$ ~ $8.64\ \text{x}10^{-7}$	0.566	1.506
15	Clay	17	5~7	25~32	7960 ~ 37811	$8.64\ \text{x}10^{-5}$	-	-
16	Clay, sand	17	1~7	25~32	15152	$8.64\ \text{x}10^{-2}$	-	-

ABH	Observed Soil Types	γ (kN/m³)	c' (kN/m²)	φ' (°)	Ey (kN/m²)	k (m/day)	cc	e_0
					~ 32836	~ 8.64 x10^{-5}		
17	Clay, sand	17	1~7	25~32	18182 ~ 33831	8.64 x10^{-2} ~ 8.64 x10^{-5}	-	-
18	Clay, sand	17	1~7	25~32	16667 ~ 34826	8.64 x10^{-2} ~ 8.64 x10^{-6}	-	-
19	Clay, sand	17	1~5	25~32	7960 ~ 50000	8.64 x10^{-2} ~ 8.64 x10^{-5}	-	-
20	Sand	17	1	25~32	18182 ~ 46970	8.64 x10^{-2}	-	-
21	Sand	17	1	25~32	10606 ~ 51515	8.64 x10^{-2}	-	-
22	Sand	17	5~7	25~28	12121 ~ 19697	8.64 x10^{-2}	-	-
23	Clay, sand	17	1~7	28~32	39394 ~ 50000	8.64 x10^{-2} ~ 8.64 x10^{-5}	-	-
24	Clay, sand	17	1~7	28~32	33333 ~ 53030	8.64 x10^{-2} ~ 8.64 x10^{-5}	-	-
25	Sand	17~18	1	25~32	15152 ~ 60606	8.64 x10^{-2}	-	-
26	Clay, sand	17~18	7	28	14925 ~ 39394	8.64 x10^{-2} ~ 8.64 x10^{-5}	0.297	1.11

3. Results and Discussion

This study analyzed settlement behavior along a proposed runway alignment constructed on soft soil. Two key settlement metrics were evaluated: operational settlement (settlement under service loads, such as aircraft operations) and total consolidation settlement, which encompasses the cumulative settlement from preloading, construction activities, and post-construction consolidation. The results highlight substantial spatial variation in settlement due to differences in subsurface soil characteristics, particularly the contrast between sandy and clayey subsoil profiles.

3.1. Settlement behavior under operational and total load

As shown in Figure 5, the maximum settlement during operational was recorded at borehole ABH-4 (STA 21+320), with a settlement of 307.1 mm. Moreover, the minimum settlement during operational is recorded at ABH-25 (STA 20+060), with a nearly negligible settlement of 2.49x10^{-3} mm. This disparity underscores the importance of soil stratigraphy on deformation behavior. Graphical results from Plaxis 2D models for ABH-4 and ABH-25 are illustrated in Figures 6 and 7, respectively, providing insight into stress distribution and deformation contours. Moreover, the maximum total settlement was also observed at ABH-4 (STA 21+320), with a total settlement of 357.97 mm. Moreover, the lowest is recorded at ABH-23 (STA 20+180), with a total settlement of 10.6 mm. The time-dependent settlement behavior, crucial for estimating post-construction maintenance needs, is illustrated in Figures 8 and 9**.** According to the Federal Aviation Administration (FAA) Advisory Circular 150/5320-6G, allowable maximum settlement for runway should not exceed ≤ 100 mm and settlement should occur gradually over time (e.g., <20 mm/year). In this case study, the maximum settlement exceeds the allowable settlement. Thus, the ground improvement must be needed to overcome the upcoming problems due to the high settlement.

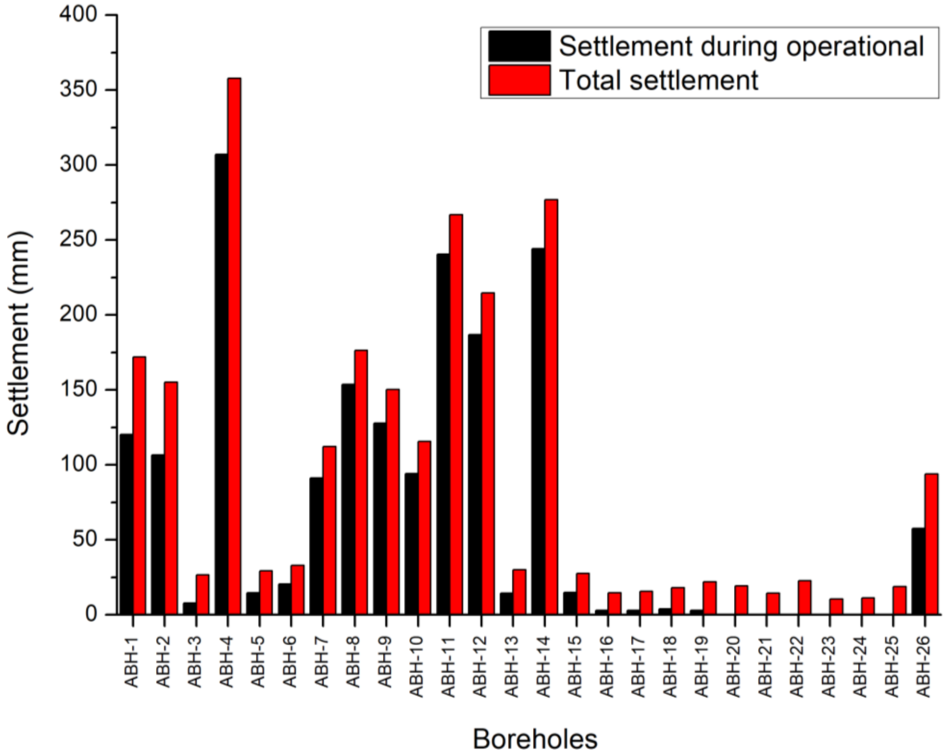

Figure 5. Settlement along the runway during the operational and the total settlement due to consolidation

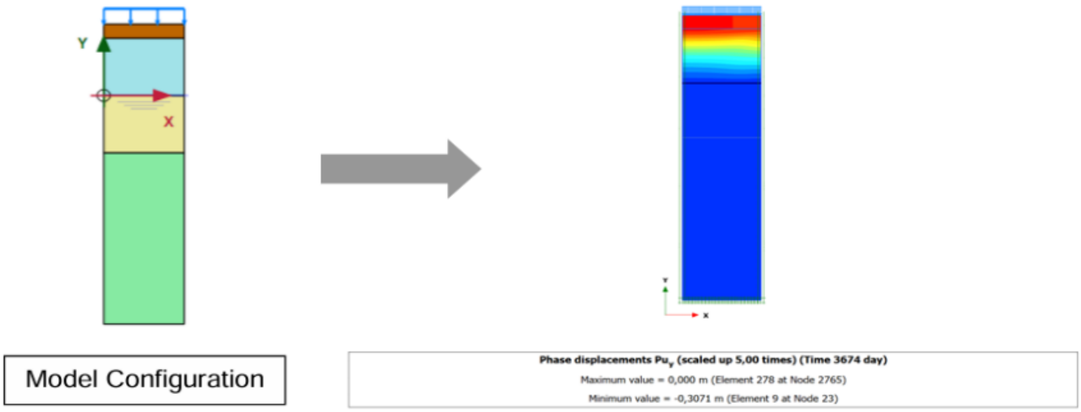

Figure 6. Model analysis (left) and the settlement result during operational (right) of ABH-04 using Plaxis 2D

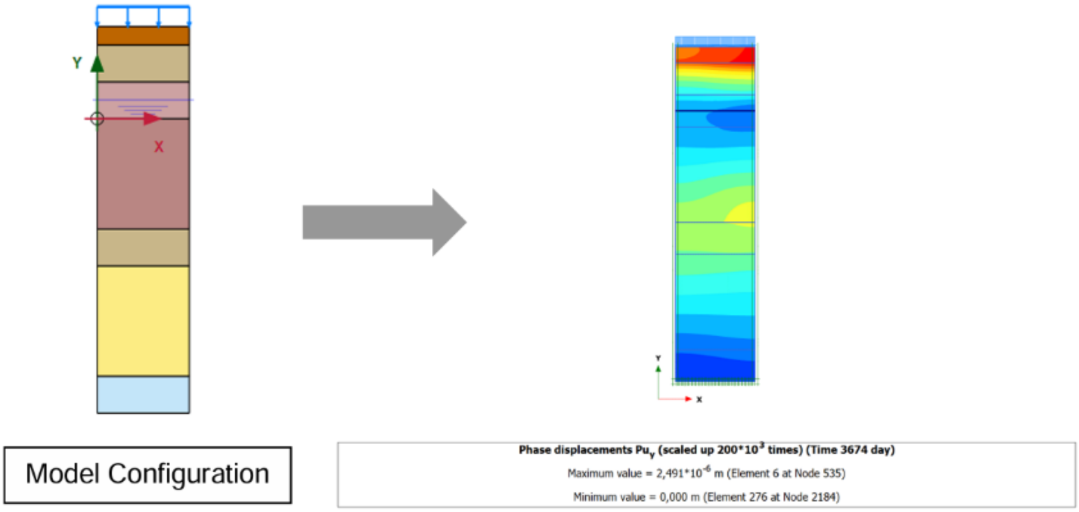

Figure 7. Model analysis (left) and the settlement result during operational (right) of ABH-25 using Plaxis 2D

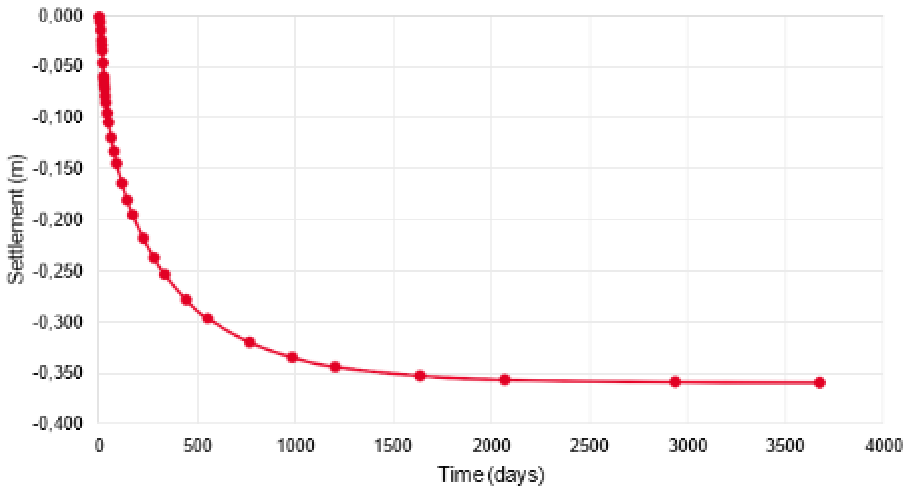

Figure 8. Settlement vs time at ABH-04

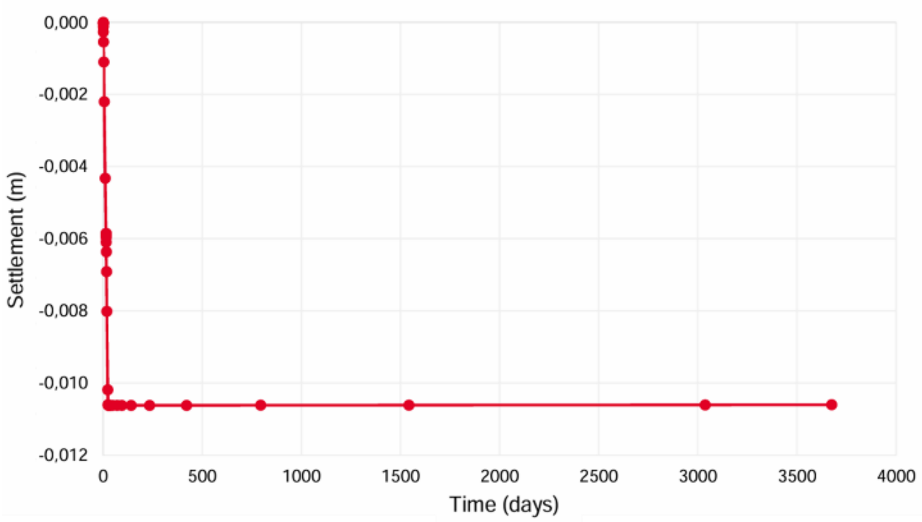

Figure 9. Settlement vs time at ABH-23

3.2. Spatial Variation of Settlement

The comprehensive settlement distribution map along the runway is presented in Figure 10. On the left side of the runway (STA 20+000 to STA 20+660) where the soil is predominated by sandy soil, the settlement values are generally small, remaining below 30 mm. However, on the right side of the runway (STA 20+660 to STA 21+500) where the soil is predominated by clayey soil, the settlement values are significantly higher, ranging between 120–250 mm, although some locations exhibit settlement below 30 mm. According to these results, the consolidation settlement is higher where the location is predominated by clayey soil as compared to the location predominated by sandy soil. These results align with previous studies [36]–[38] which demonstrated that clayey soil typically exhibits higher consolidation potential and prolonged settlement durations due to low permeability and high compressibility. According this result, the differential settlement along the runway is exceed the allowable differential settlement from FAA Advisory Circular 150/5320-6G which is ≤ 30 mm over 45 m.

Figure 10. Distribution map of the total settlement

4. Conclusion

This study presents a numerical analysis of settlement due to consolidation for runway construction on soft soil. The findings highlight significant variations in settlement across different locations along the runway, influenced by soil composition.

1. During the operational phase, the highest settlement was observed at ABH-4 (307.1 mm), while the lowest occurred at ABH-20 (2.491 $\times 10^{-3}$ mm). Total consolidation-induced settlement showed a maximum value at ABH-4 (357.97 mm) and a minimum at ABH-23 (10.6 mm).
2. The distribution of total settlement along the runway varied based on soil characteristics. Sections with predominantly clayey soil exhibited greater settlement, whereas areas with sandy soil experienced significantly lower settlement.
3. The observed maximum settlement and differential settlement exceeded allowable thresholds based on international guidelines, indicating a critical need for ground improvement measures to ensure long-term performance and structural safety.

These findings emphasize the importance of assessing soil properties before runway construction to mitigate excessive settlement. Future studies should incorporate long-term field monitoring data to validate and calibrate numerical models more accurately and advanced ground improvement techniques to enhance the stability and longevity of runways built on soft soil.

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