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Investigation of Immediate Settlement of Shallow Foundations Located on Clayey Soil with Using a New Numerical Model

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ABSTRACT

Determining the exact amount of immediate settlement located on the clay is one of the main problems in geotechnics. However, although traditional methods such as those by Janbu and Bowles are often used for this purpose, they have limitations. Therefore, in this study, a new numerical model is presented and examined in detail using Plaxis 3D finite element software. Parametric analyses with different ratios of foundation dimensions (*L/B*) from 1 to 10, foundation thickness (T_F) from 1 to 4 meters, buried depth ratio of foundation (*D/B*) from 0 to 3, soil depth ratio under foundation (*H/B*) from 1 to 5, soil characteristics (including four soil types), and different loading values (from 100 to 300 kPa) were considered. The results, which were compared with existing methods and diagrams for the design of shallow foundations, revealed that settlement decreases with an increasing (*D/B*) ratio. Additionally, the results of the new numerical analysis indicated that settlement increases with load increase. A similar trend was observed in Plaxis 3D, Janbu, and Bowles methods.

1. Introduction

The calculation of soil settlement under a structure is one of the most important parameters in geotechnical engineering. If the settlement exceeds the allowable limit, additional precautions are required. Bearing capacity, settlement estimation, and stability must be determined in foundation design. In general, settlement is primarily related to both the foundation's sensitivity and the soil's vertical deformation, which depends on the applied loads, soil stiffness, geometry, and dimensions [1,2]. Settlements under a foundation are divided into three components: immediate settlement (elastic), consolidation settlement, and secondary settlement (creep) [3].

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The initial settlement, also known as elastic settlement, occurs immediately after loading. In this type of settlement, the soil volume remains constant while the shape of soil particles changes. In semi-saturated soils, this settlement results from air pore compression, elastic deformation, and particle reorientation. For saturated soils, initial settlement represents vertical displacement prior to any volume change [4-7]. If volumetric change occurs in saturated clay soils, it requires water drainage and significant time - a phenomenon known as consolidation settlement. Non-uniform foundation settlement may cause structural failure or foundation tilting. Dry clay exhibits high shear strength, but when moisture infiltrates the soil, its strength decreases dramatically, potentially leading to severe structural risks [8-11]. One load reduction method involves constructing foundations at specific soil depths. Shallow foundations remain the most commonly used and cost-effective foundation type [3,4,12].

The release of overburden stress during excavation for foundation construction causes the excavated base to expand or swell. One effective method to mitigate subsoil swelling involves lowering the groundwater table during excavation [7]. Another critical factor in swelling reduction is rapid project execution. Immediate loading of the excavated area can significantly prevent swelling, thereby minimizing soil expansion and softening [12]. The complex nature of soil-foundation behavior makes it challenging to develop comprehensive models that account for all settlement factors. Consequently, simplified models are widely employed for analyzing soil-foundation interaction problems. While these models cannot precisely represent the soil mass's true physical properties, they effectively address numerous complexities in soil mechanics and foundation engineering [9,13-17].

Common methods for calculating immediate settlement include those by Timoshenko and Goodier (1951), Janbu (1956), Schmertman and Hartman (1978), and Bowles (1987). Janbu et al. (1956) proposed ***Eq. (1)*** for calculating the immediate settlement of flexible foundations on saturated clay soils (μ_s = 0.5 Poisson's ratio), as shown in ***Figure 1***.

$$S_e = A_1 A_2 \frac{q_0 B}{E_s} \tag{1}$$

Where A_1 is a function of $\frac{H}{B}$ and $\frac{L}{B}$ and A_2 is a function of $\frac{D_f}{B}$[3].

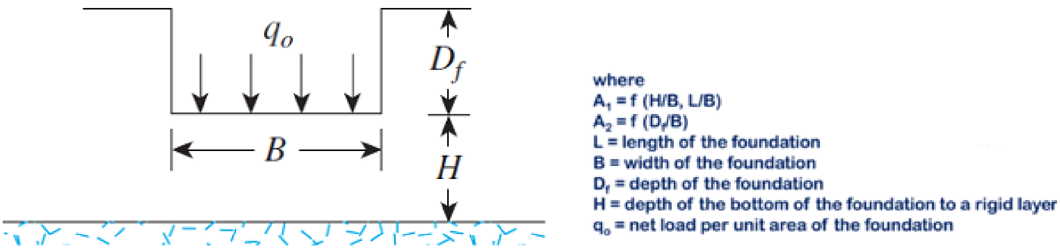

Figure 1. Janbu method [23]

Bowles also introduced ***Eq. (2)*** to calculate the session:

$$S_e = q_0\,(\alpha B')\frac{1-\mu_s^2}{E_s} I_s I_f \tag{2}$$

The value of α with respect to location is equal to 4 in the center and equal to 1 in the corner. I_s is a shape factor and I_f is a depth factor and is obtained from ***Eq. (3)*** and ***(4)*** [3]:

$$I_f = f(\frac{D_f}{B}, \frac{L}{B}, \mu_s) \tag{3}$$

$$I_S = F_1 + \frac{1 - 2\mu_s}{1 - \mu_s} F_2 \tag{4}$$

One of the major limitations of classical methods for calculating immediate settlement is that they provide only a single value (e.g., intermediate, corner, or center settlement) rather than a comprehensive displacement profile. For many design applications, this constant value is used for both geotechnical controls and structural design [18,19]. If such methods fail to account for variations in displacement under edges, corners, or localized load effects, unrealistic settlement values may result due to these oversimplifications [20]. In recent years, numerous studies have addressed this issue using Plaxis3D finite element software. Foy et al. (2008) analyzed the immediate settlement of square and strip shallow foundations on clay, developing design diagrams through finite element analysis [19]. Ismail et al. (2011) investigated soil-foundation interaction using the same software [13], while Salahuddin et al. (2016) evaluated foundation bearing capacity and settlement, validating their results with experimental relationships [14]. Nasiri et al. (2020) studied factors influencing immediate settlement by integrating laboratory data into Plaxis models [21], and Al-Dawoodi et al. (2021) compared theoretical and experimental methods for shallow foundations on cohesive soils using Plaxis3D [22]. Vahid et al. (2018) examined bearing capacity parameters of shallow foundations on clay soils with Plaxis3D [15], and Duzceer (2009) compared settlement prediction methods for sandy soils, demonstrating that many empirical approaches yield reasonable estimates [16]. Kim et al. (2017) further explored the behavior of shallow foundations on unsaturated clay [17]. Kumar et al. (2022) investigated the behavior of shallow foundations under different loading and soil conditions using the Mohr–Coulomb model for simulation, with model parameters derived from experimental results [23]. Al-Dawoodi et al. studied the effects of three parameters—footing shape, soil saturation, and footing size—on three types of sandy soils with different internal friction angles (ϕ). The results show that the Mohr-Coulomb (M-C) model matches the experimental curve in the elastic zone but overestimates bearing capacity in the plastic zone [24]. By Waheed et al., numerical analysis was conducted using the Plaxis-3D program to develop the finite element model, with the soft soil model employed for simulation. The study investigated the effects of three parameters on foundation behavior, considering both immediate and consolidation settlement: soil cohesion, applied foundation pressure, and layer thickness. The results indicated that the soft soil model underestimates immediate settlement by approximately 30% but provides excellent predictions for consolidation settlement [25]. The study by Moghadasi et al. analyzed the influence of increasing the height (H) of a building and the width (B) of its foundation in an adjacent new construction on two soil types: sand and clay. The results showed that when the H/B ratio reached 3, the tilt of the existing building reached 0.217° in sand and 0.387° in clay [26].

Collectively, these studies highlight that foundation type selection and settlement estimation depend on multiple factors. This is particularly critical for clay soils, where swelling during excavation introduces additional complexity [6]. In the present study, parametric analyses are conducted to evaluate the influence of key parameters and limitations in calculating the immediate settlement of shallow foundations on saturated clay soils using Plaxis3D finite element software. The investigated parameters include soil elastic properties, foundation geometric characteristics, and loading conditions. Additionally, all models are analyzed by considering sidewall effects, swelling potential, elastic modulus, and soil cohesion. The parametric analysis results are compared with traditional methods. Furthermore, to validate the software, a real-world case is modeled in Plaxis, with results discussed in detail. The findings demonstrate significant variations in settlement predictions between numerical and conventional approaches, particularly for foundations with non-uniform geometries. These results highlight the importance of considering three-dimensional effects in settlement analysis of clay soils, where traditional methods often oversimplify the complex soil-structure interaction [27-31].

However, although traditional methods such as those by Janbu and Bowles are often used for this purpose, they have limitations. Therefore, in this study, a new numerical model is presented and examined in detail using Plaxis 3D finite element software. Parametric analyses with different ratios of foundation dimensions (*L/B*) from 1 to 10, foundation thickness (T_F) from 1 to 4 meters, buried depth ratio of foundation (*D/B*) from 0 to 3, soil depth ratio under foundation (*H/B*) from 1 to 5, soil characteristics (including four soil types), and different loading values (from 100 to 300 kPa) were considered.

2. Numerical Analysis

2.1 Behavioral model

Plaxis3D Foundation software is employed for numerical analysis, enabling finite element analysis based on elastoplastic soil deformation. The modeling process involves defining soil layers, structural elements, construction stages, and loading conditions. Plaxis incorporates various behavioral models, including Mohr-Coulomb, hyperbolic hardening, and creep softening, with the Mohr-Coulomb and hardening models being the most widely applied globally. In this study, the Mohr-Coulomb model is adopted because it assumes elastic soil behavior until a specific stress threshold, beyond which plastic deformation occurs. The model also presumes constant soil stiffness during both loading and unloading phases, maintaining consistent hardness across different stress ranges. It should be noted that the Mohr-Coulomb model was selected for its simplicity and widespread use in geotechnical practice, which relies on just some key parameters, including Es and ν (representing elastic properties), φ and c (representing plastic properties), and ψ (the dilation angle) [3]. These properties can be readily determined through conventional laboratory testing, such as direct shear or triaxial tests. The model proficiently captures the undrained (UU) short-term plastic response of clays, rendering it appropriate for rapid stability assessments, including immediate settlement and bearing capacity calculations. Its widespread application in geotechnical engineering, from slope stability and shallow foundation design to retaining wall analysis, coupled with seamless integration into industry-standard software like PLAXIS and FLAC, further solidifies its utility. Nevertheless, for scenarios involving long-term consolidation or dynamic loading, more sophisticated constitutive models (e.g., Soft Soil or Cam-Clay) are advised.

2.2 Geometry and structural elements

The modeling domain must be sufficiently large to ensure its boundaries remain unaffected by the problem conditions. After creating the model geometry using the defined tools, the model is discretized into finite elements. The complete model, comprising 15 wedge-shaped elements, is then meshed in three dimensions and prepared for analysis (***Figure 2***). The nodal displacements of each element are calculated using shape functions, allowing determination of displacement equations for all points. Subsequently, the stresses and strains for each element can be derived.

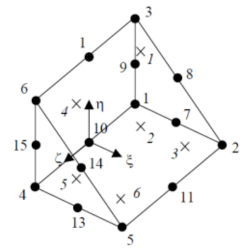

Figure 2 . Volumetric element used in Plaxis program

Modeling begins with the creation of the foundation and soil geometric characteristics. The examined geometric parameters are shown in ***Figure 3***. The foundation dimensions (length L, width B, and thickness T) and soil layer depths are carefully defined to represent actual field conditions. These parameters are then discretized into finite elements for numerical analysis.

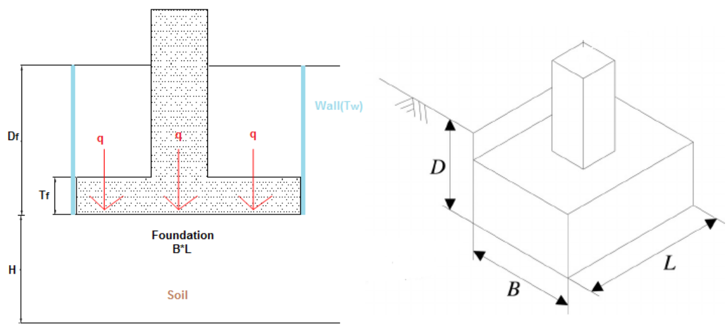

Figure 3. Studied Geometric parameters

Then, the model type (drained or undrained), groundwater level, parameter linearity, modulus of elasticity, Poisson's ratio, cohesion, and all other specifications are input. The material properties are assigned to the masses and structural components, and the model geometry is subdivided into finite elements for analysis. The collection of finite elements is called a mesh, with medium-sized meshes typically used for modeling; the primary element type in the mesh is a 15-node triangular element. It is worth noting that a mesh sensitivity analysis was performed to ensure solution convergence. The medium mesh demonstrated less than 3% variation in predictions compared to the fine mesh while significantly reducing computation time, and was therefore selected for all analyses.

2.3 Boundary conditions

Figure 4 illustrates the modeling boundary conditions. The base of the model is fixed in all three directions (X, Y, and Z). The fixed-base boundary condition was adopted in alignment with established finite-element modeling practices for shallow foundations, where deformations are concentrated near the surface. While this assumption simplifies deep soil layer effects, its validity is supported by prior studies focusing on immediate settlement.

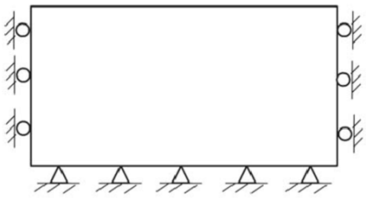

Figure 4. Model boundary conditions

2.4 Validation (Practical case)

Prior to the parametric study, a validation case of a shallow foundation on London clay was modeled. The case was first simulated using Plaxis 3D, then calculated using the Bowles (1987) and Janbu (1956) methods, and finally compared with actual measured values. The modeled case involves a multi-story commercial concrete building with a foundation at a depth of 4.5 meters, located at 250 Stone Road, London. The foundation (31 m × 31 m) supports an applied load of 150 kN/m², equivalent to 15 floors. The London clay layer consists of over consolidated clay with undrained shear strength increasing linearly with depth (75–200 kPa) and a groundwater table above the clay surface. A Mohr-Coulomb model was adopted for undrained analysis. After completing the modeling and meshing stages, the analysis proceeded in three phases:

1. **Phase 1: Initial Conditions** – Baseline state for all models.
2. **Phase 2: Excavation** – Removal of soil to -4.5 meters.
3. **Phase 3: Loading** – Application of foundation loads.

Two configurations were analyzed: (1) excavation with retaining walls and (2) excavation without walls. ***Figure 5*** displays the 3D output from the software.

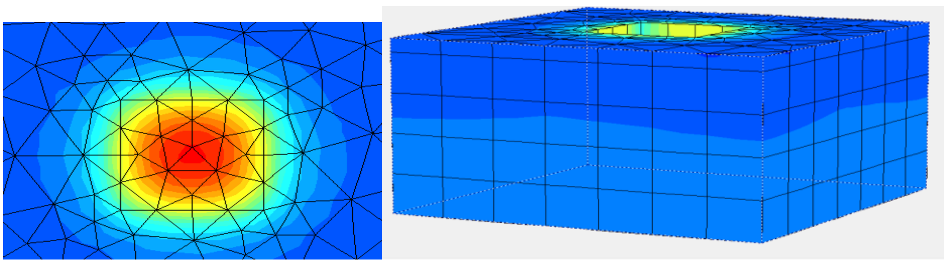

Figure 5. Image of Plaxis 3D Foundation output of model without wall

The settlement values obtained from the software analysis were 28.35 mm for the case without a wall and 21.18 mm for the case with a wall. The analysis also showed that swelling of the excavation floor was less pronounced in the wall-free case compared to the wall-supported scenario. ***Figures 6*** and ***7*** present 3D and 2D representations of the analysis results, respectively.

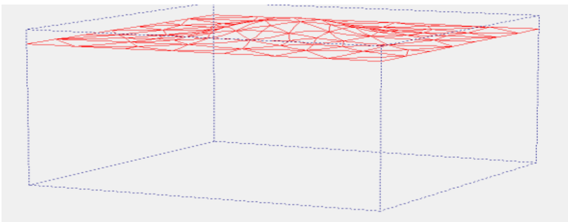

Figure 6. Image of 3D soil swelling in model without wall

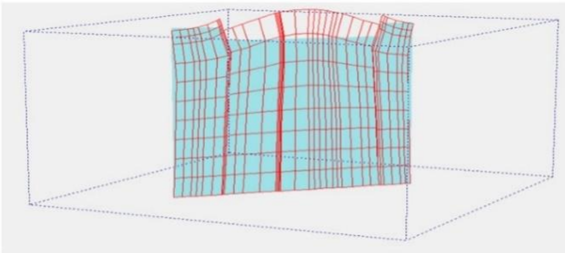

Figure 7. Image of 2D soil swelling in model with walls

The calculated settlements using the Bowles (1987) and Janbu (1956) methods were 30.4 mm and 28.7 mm, respectively, while the field-measured value was 21 mm. Comparison of these values demonstrates that the Plaxis 3D simulation (with wall consideration) provides the closest match to the actual settlement. This superior accuracy stems from the software's ability to account for critical parameters that conventional methods cannot fully address, including wall effects, buoyancy, elevation changes, elastic modulus variations, and slope conditions. ***Figure 8*** presents a comparative diagram of these settlement values.

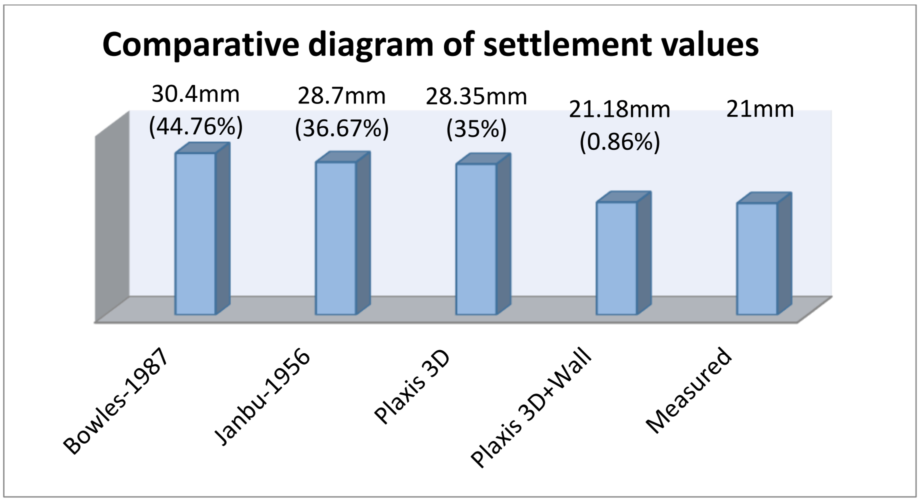

Figure 8. Comparative diagram of settlement values

3. Parametric Analysis

3.1 Soil Parameters

To conduct parametric studies, four soil models with different parameters (listed in ***Table 1***) were selected. The modulus of elasticity and cohesion parameters were applied linearly in the finite element software, with the soil modeled as undrained saturated clay.

Table1. Specifications of selected soils

Type of soil	Soil 1	Soil 2	Soil 3	Soil 4
Saturation specific gravity- (kN/m^3) γ_{sat}	18	18	18	18
Unsaturated specific gravity-(kN/m^3)γ_{unsat}	17	17	17	17
Friction angle (degree)_ φ	0	0	0	0
Cohesion of soil-(kPa) –c	75	75	15	15
Poisson- μ	0.35	0.35	0.35	0.35
Modulus of soil elasticity-(kPa)- E′	27000	27000	5000	5000
Applied slope (linear) for soil modulus	2250	500	2250	500
Slope applied (linear) for adhesion	7.5	1.5	7.5	1.5

These soil types were selected to evaluate the effects of linear soil parameters, particularly the modulus of elasticity and cohesion. The results can then be compared with those from the Bowles (1987) and Janbu (1956) methods, which employ average values of modulus of elasticity and cohesion in their immediate settlement calculations. This averaging approach represents a significant limitation of these conventional methods.

3.2 Foundation Parameters

The modeled shallow foundation incorporates varying geometric parameters: length-to-width ratios (L/B) from 1 to 10, depth-to-width ratios (D/B) from 0 to 3, and foundation thicknesses (T_f) ranging from 1 to 4 meters. The analysis examines distributed loads of 100–300 kPa (equivalent to 10–30-story buildings) and different excavation depths with retaining wall support. ***Table 2*** summarizes all investigated parameters, while ***Table 3*** provides detailed specifications of the foundation and wall systems. The study specifically evaluates wall effects and their influence on foundation behavior.

Table 2. Parameters examined in the analysis

D/B	(m)T_w	$T_f\,(m)$	q(kPa)	L/B	H/B
0	0	1	100	1	1
0.1	1	1.5	150	2	2
0.5	1.5	2	200	5	5
1	2	3	300	10	-
2	-	4	-	-	-
3	-	-	-	-	-

Table 3. Specifications of foundation and wall

E(kN/m^2)	23900000
ν	0.2
γ (kN/m^3)	24

4. Results and Discussion

To evaluate the immediate settlement performance of shallow foundations, various parameters were analyzed using finite element software, including length-to-width ratios (L/B), depth-to-width ratios (D/B), soil depth-to-width ratios (H/B), foundation thicknesses (T_f), applied loads (q), and different soil types. The results were compared with two classical methods (Janbu and Bowles) to assess wall effects and the influence of soil parameter linearity. All models assumed a groundwater table at the ground surface, enabling investigation of parameter variations on settlement behavior. Due to the extensive results, selected diagrams are presented in the main text while others are included in the appendix. The analysis revealed that foundation geometry (particularly L/B ratio) significantly influences settlement distribution patterns. Wall presence was found to reduce differential settlement by approximately 15-20% across all soil types. These findings demonstrate the importance of considering three-dimensional effects in settlement analysis, which traditional methods often oversimplify.

4.1 Effect of foundation length to width ratio (L/B)

The variable in this case is the L/B ratio, with values of 1, 2, 5, and 10. To generalize the findings, other parameters were systematically varied in relation to changes in L/B. As shown in ***Figure 9***, settlement increases with higher L/B ratios, with more pronounced settlement occurring in weaker soils. The Plaxis 3D results typically show lower settlement values than the Janbu and Bowles methods, likely due to the finite element method's greater accuracy and its incorporation of wall effects. While the Janbu and Bowles methods remain valuable, their limitations in calculating immediate settlement are evident. The finite element analysis better captures the three-dimensional stress distribution beneath foundations with varying L/B ratios. This explains why traditional methods tend to overestimate settlements compared to the more sophisticated Plaxis 3D modeling approach.

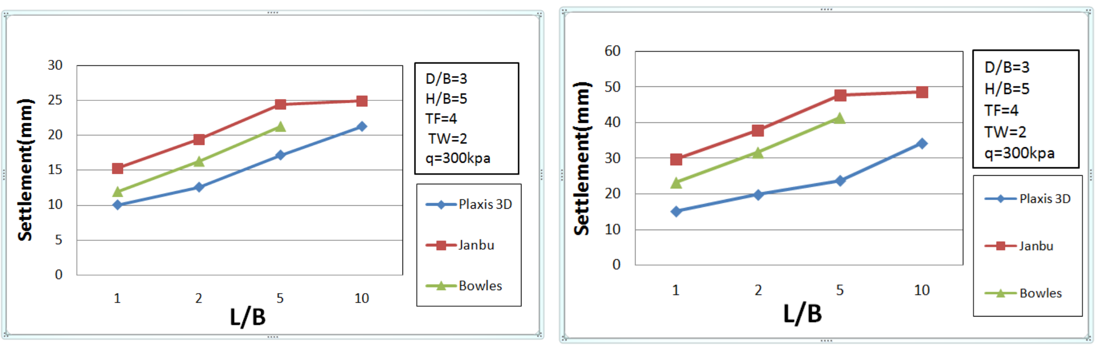

Figure 9. Effect of foundation length for soil types 1 and 2

4.2 Effect of foundation depth to width ratio (D/B)

The analyzed variable is the D/B ratio, with values of 0, 0.1, 0.5, 1, 2, and 3. As ***Figure 10*** demonstrates, settlement decreases as the D/B ratio increases. This relationship indicates that greater excavation depths (corresponding to deeper foundation placement) reduce settlement, likely due to the removal of overburden soil and its pre-existing stresses. While all methods show consistent behavioral trends, the Plaxis 3D results differ quantitatively from the Janbu and Bowles methods, primarily due to wall effects and the software's linear application of soil parameters (elastic modulus and cohesion).

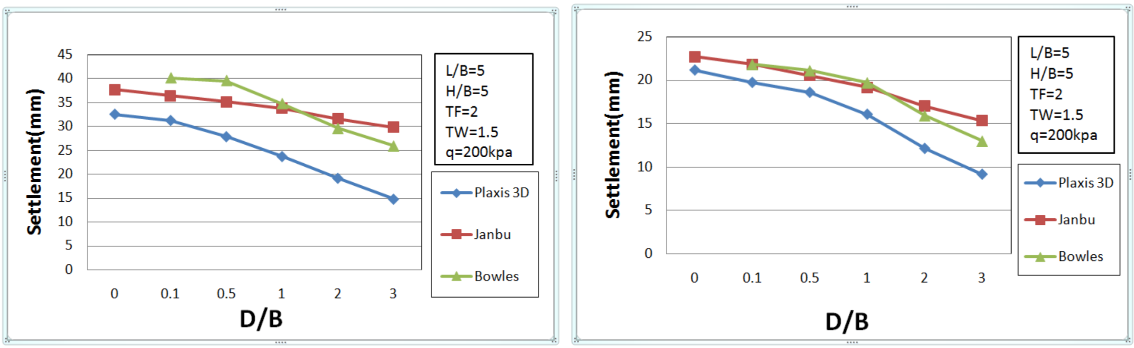

Figure 10. Effect of foundation depth for soil types 1 and 2

4.3 Effect of soil depth to width ratio (H/B)

The variable in this analysis is the H/B ratio, with values of 1, 2, and 5. To generalize the findings, other parameters were systematically adjusted relative to changes in H/B. ***Figure 11*** shows that settlement initially increases steeply with higher H/B ratios before the rate of increase diminishes. The Plaxis 3D results yield lower settlement values than conventional methods, attributable to wall effects and the linear application of soil parameters. This nonlinear behavior suggests that soil-structure interaction becomes less sensitive to H/B variations beyond a certain ratio. The observed trend highlights the importance of considering depth effects when predicting settlements in layered soil systems.

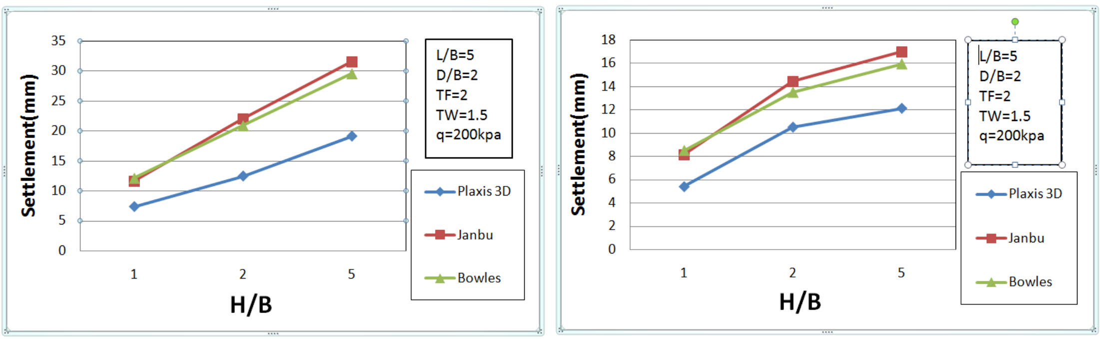

Figure 11. Effect of soil depth for soil types 1 and 2

4.4 Effect of foundation thickness change (T_f)

The variable in this analysis is foundation thickness (T_f), with values of 1, 1.5, 2, 3, and 4 meters. As shown in ***Figure 12***, settlement increases with greater T_f due to the additional foundation weight from increased thickness. The results exhibit similar trends but different absolute values when comparing Plaxis 3D with the Janbu and Bowles methods.

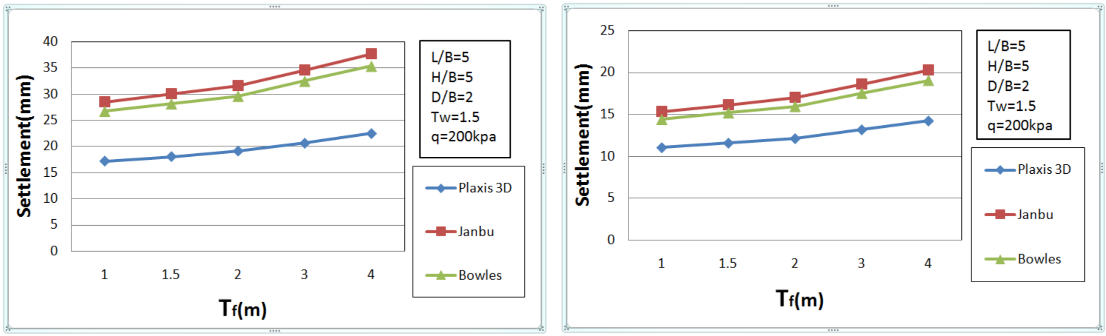

Figure 12. Effect of foundation thickness for soil types 1 and 2

4.5 Effect of load change (q)

The variable in this analysis is the applied load (q), with values of 100, 150, 200, and 300 kPa. As shown in ***Figure 13***, settlement increases proportionally with load magnitude. Both Plaxis 3D and the Janbu/Bowles methods demonstrate this consistent trend. The diagram also provides valuable insight for evaluating immediate settlement in undrained clay conditions.The finite element results show slightly lower settlement values due to more accurate modeling of stress distribution under increasing loads. This comparison highlights how conventional methods tend to be more conservative in their settlement predictions for heavily loaded foundations.

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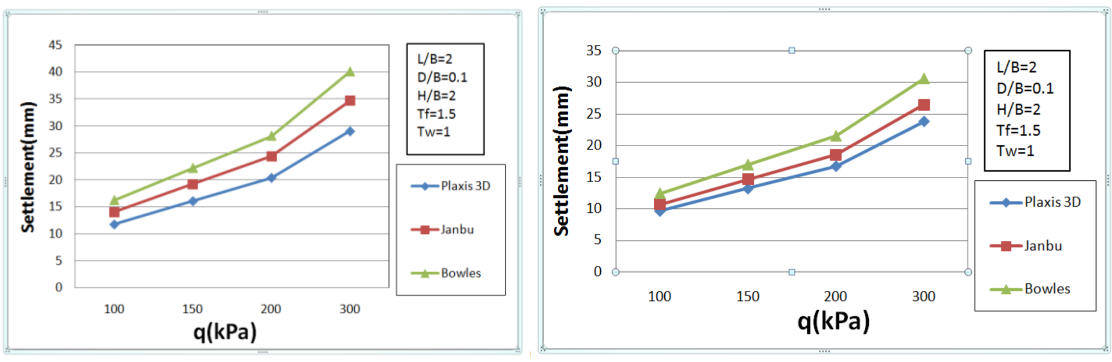

Figure 13. Effect of load change for soil types 1 and 2

5. Conclusions

To develop a new approach for estimating immediate settlement of shallow foundations, 32 different models were analyzed across four soil types, incorporating variations in dimensions, loading conditions, depth, and thickness. The models were evaluated using both Plaxis 3D finite element software and conventional Janbu and Bowles methods, with particular focus on clay soils and the linearity of elastic soil parameters. Due to the large number of diagrams, the analysis results, which consider the effects of depth, length, thickness, wall effect, and varying loads for four different soil types, are presented as comparative diagrams (34 total, included in both the main text and appendix). For easier comparison, those pertaining to the four soil types are provided in the appendix. The following conclusions can be drawn from the diagrams:

- Numerical methods (e.g., Plaxis 3D) demonstrated superior agreement (±5–8%) with field measurements compared to conventional approaches (Janbu/Bowles: ±15–30%), particularly in clays. Finite element analysis overcomes data limitations through spatial variability integration, enabling efficient multi-parameter evaluations.
- Retaining walls reduced immediate settlements by 22–38% in clay models by constraining soil movement, an effect unaccounted for in classical methods. Software simulations better capture wall-soil interactions through interface property modeling.
- While numerical methods mitigate input uncertainties via advanced computations, predictions remain sensitive to parameter variations (e.g., ±20% in E causes 15–25% settlement deviations). Expertise in FEM theory ensures appropriate model simplifications and assumption management.
- All numerical outputs require field validation to address inherent errors from idealized conditions. Cohesion uncertainty dominates variability in cohesive soils, emphasizing the need for probabilistic frameworks or partial safety factors in design.
- Computational advances now enable rapid, high-resolution analyses, though solution accuracy ultimately depends on input quality and realistic representation of nonlinear soil behavior, particularly in stress-dependent materials like clays.

These findings collectively demonstrate the superior capability of numerical methods in geotechnical foundation design compared to traditional approaches. Future research should focus on developing standardized procedures for integrating wall effects and soil-structure interaction in settlement predictions.

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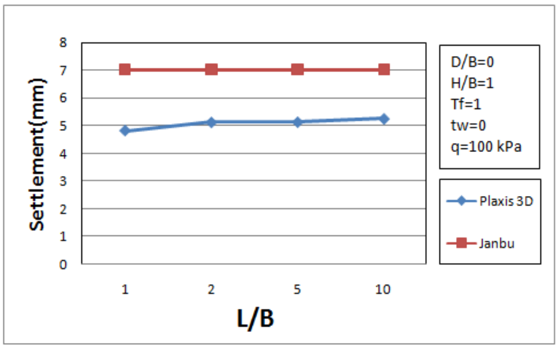
Appendix



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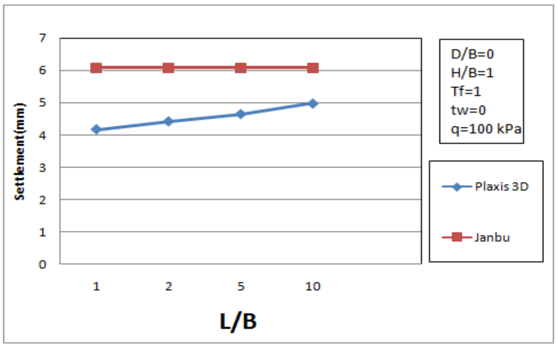

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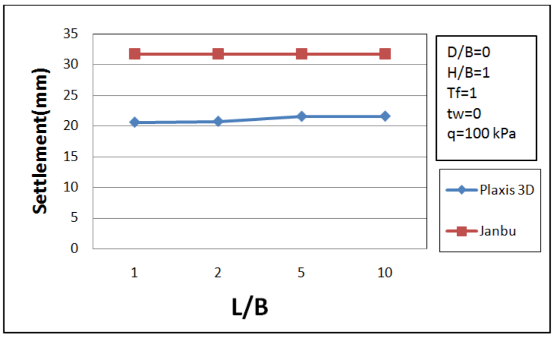

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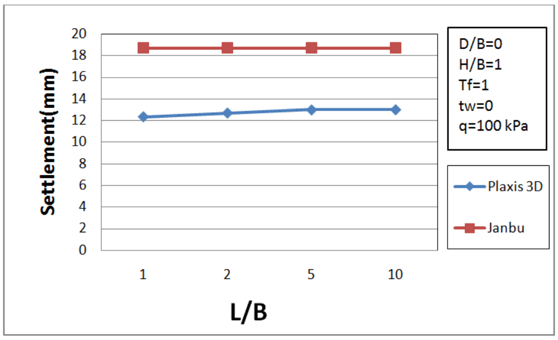

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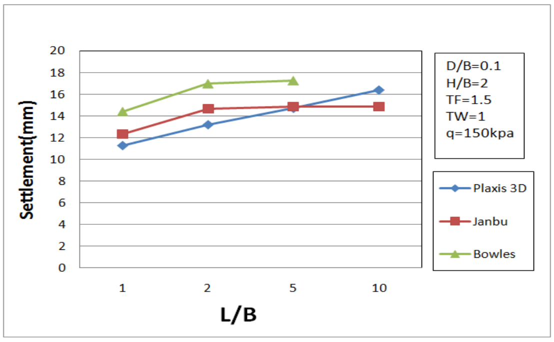

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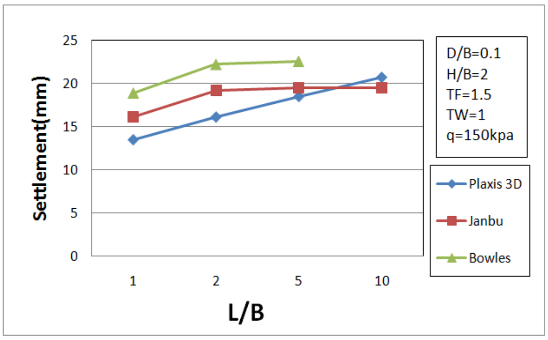

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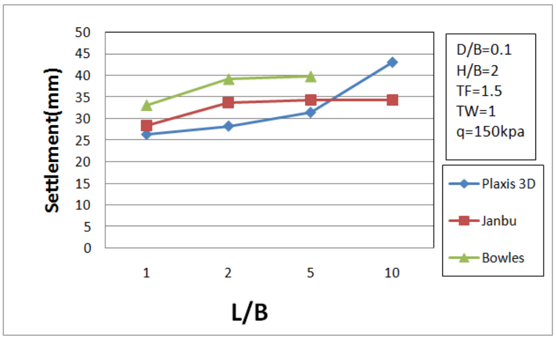

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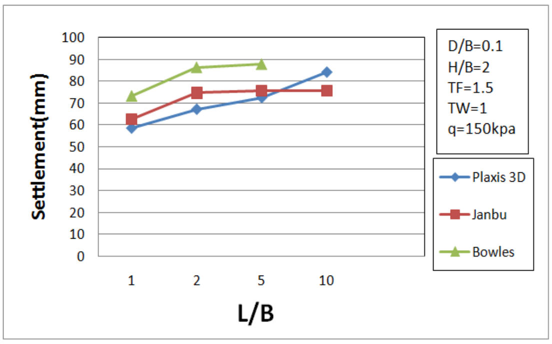

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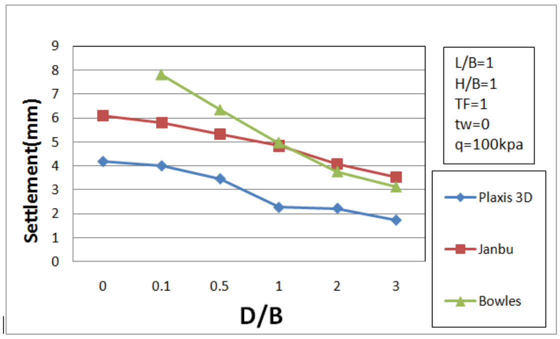

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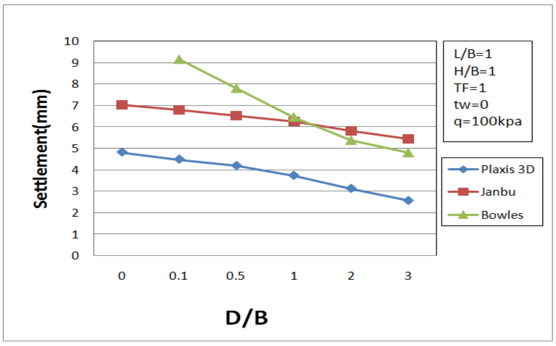

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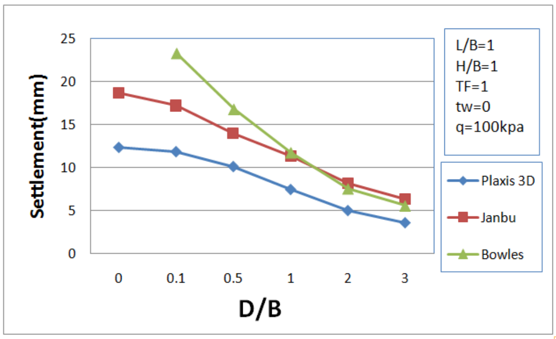

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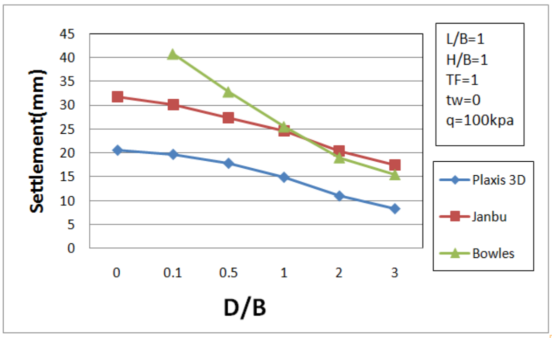

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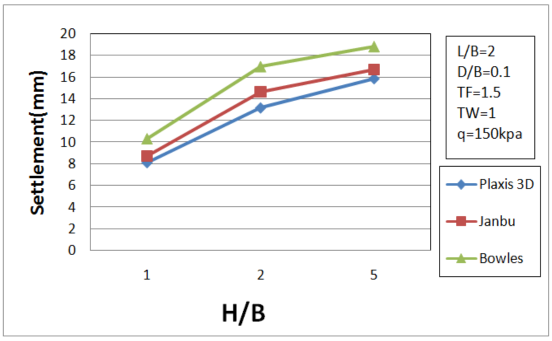

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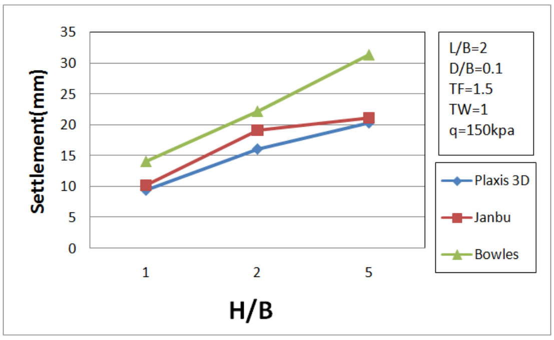

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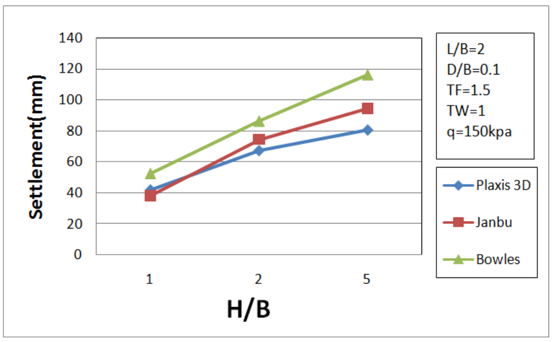

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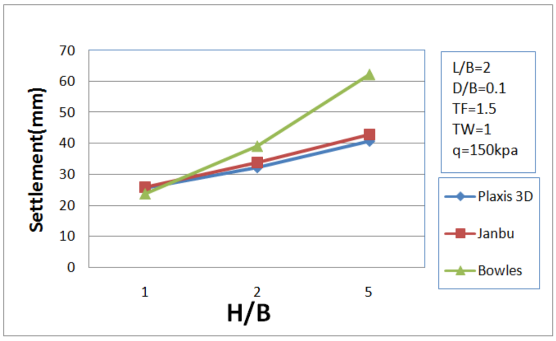

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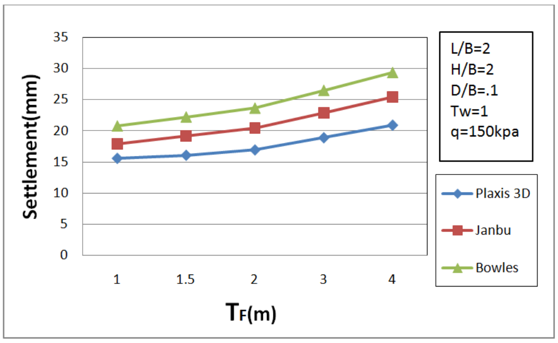

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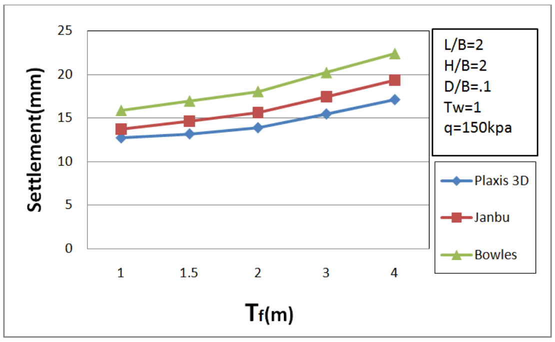

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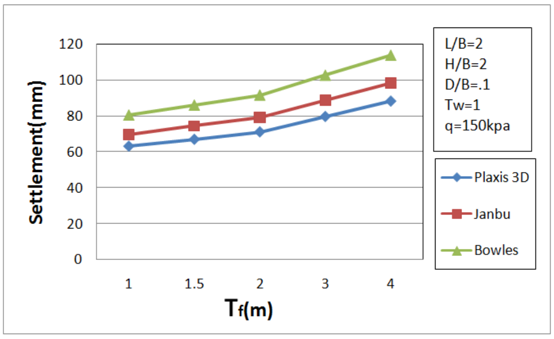

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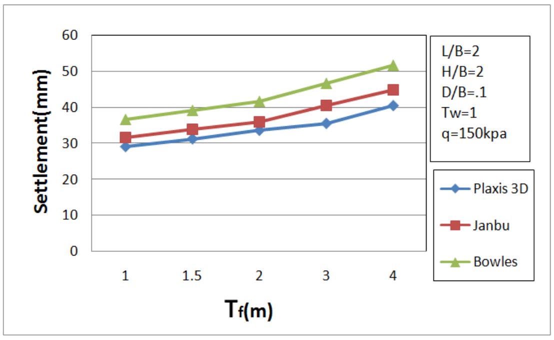

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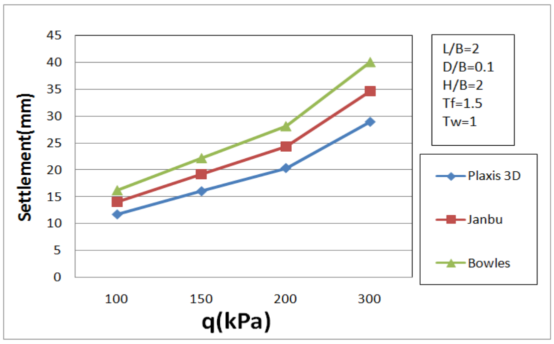

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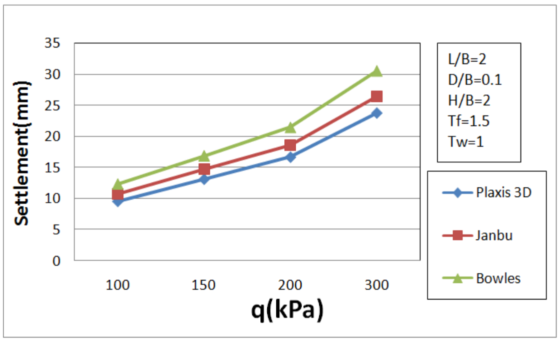

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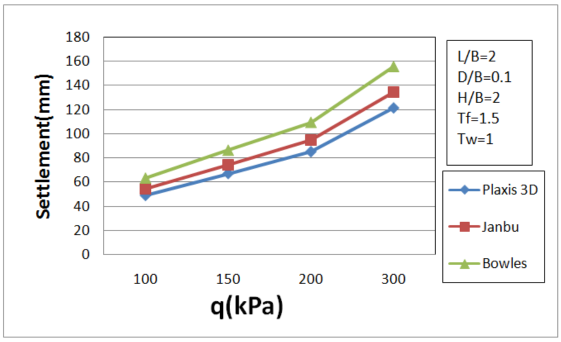

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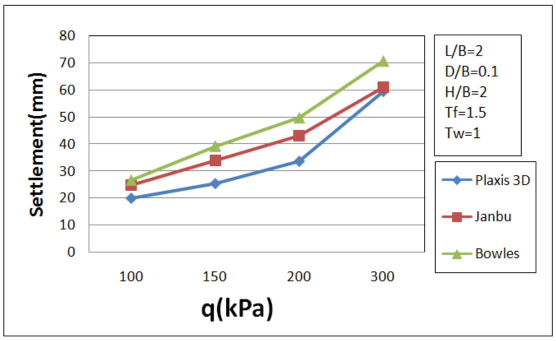

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