NUMERICAL MODELLING OF SHALLOW FOUNDATION ON EXPANSIVE SOIL UNDER WET AND DRY CYCLES

Muhammad Rehan Hakro[1*], Mohammad Ahsan Channa[2], Imtiaz Ali Hakro[3]

Abstract

The research paper investigates the behaviour of shallow foundations on expansive shale soil under varying hydrological conditions, such as rainfall and drought. Expansive soil experiences volumetric changes due to fluctuating water conditions, resulting in differential movements of foundations. Previous studies on user-defined swelling rock models have predominantly addressed tunnel behaviour. This study extends the application of such models to simulate more realistic field conditions, focusing on the deformation and load-bearing response of shallow foundations subjected to swelling pressures under varying geotechnical and environmental conditions. The new use of the User Defined Swelling Rock Model in Plaxis 2D FEM software allowed settlement and swelling to be simulated under realistic conditions, such as varying soil saturations, stages of loading, dry-wet cycles, and time-dependent evolution of swelling. Settlement and swelling computations were simulated using Plaxis 2D FEM software under different soil saturation, loading, and rainfall conditions. The first part of the study was to determine the swelling characteristics of expansive soil of study area of Jamshoro and model parameters such as cohesion, angle of internal friction, swelling pressure, swelling potential and modulus of elasticity. Laboratory testing and calibration was also performed to determine the model parameters. After this numerical modelling was performed with swelling rock model to observe the heaving of shallow foundation due to swelling of expansive soil in wet conditions. Modelling in Plaxis 2D conducted model studies with a 100 kPa foundation pressure on shale soil, followed by unloading and saturation. Short-term heaving remained within tolerable limits. However, over 100 days, extensive vertical movement exceeding the tolerable limit was observed due to continuous shale swelling. Rapid water table increase caused significant vertical movement, but gradual rise reduced it. The depth of the shale layer, underlain by stiff limestone, significantly influenced foundation movement, even at 1 meter depth causing intolerable movements.

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[1,3]Mehran University of Engineering & Technology, Sindh Pakistan.

[2]Sindh Agricultural University Tandaojam, Sindh, Pakistan.

****Corresponding author:***
Rehan.hakro@faculty.muet.edu.pk

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1.0 INTRODUCTION

Expansive soils, also known as swelling soils, pose significant challenges to the construction industry worldwide. These unique types of soils exhibit substantial volume changes in response to variations in moisture content, causing detrimental effects on infrastructure, especially shallow foundations. Shallow foundations transmit the entire structure's load to the soil at a relatively shallow depth. The design of shallow foundations primarily revolves around considerations of settlement, heaving, and bearing capacity. In many instances, settlement takes precedence over bearing capacity when designing shallow footings. Nevertheless, in certain situations, expansive-related heaving and settlement caused by shrinkage may also be significant factors to consider. Buildings erected on expansive soil may experience significant deformation or pressure due to soil swelling, leading to potential harm to their structural integrity (Elarabi, 2012). In Pakistan, expansive soils are widespread and have led to significant structural damage in various regions, including cracks in single- and double-story buildings and the uplift of floor slabs (Farooq, 1996) (Akbar & Farooq, 2002). To mitigate these issues and reduce repair expenses, engineering designs must consider and address the impacts of soil swelling (Lim & Siemens, 2016). The unpredictability of their behaviour makes it imperative to comprehensively study and understand their interactions with foundation systems. A suggested explanation for soil swelling involves the interlayer expansion of the clay mineral Montmorillonite. The unique molecular structure of Montmorillonite attracts and retains water molecules between its clay crystal sheets. When potentially expansive soils become saturated, Montmorillonite can absorb significant quantities of water into the gaps between its clay sheets. This absorption causes the sheets to separate further, resulting in an increase in soil pressure or expansion of soil volume. Conversely, soil swelling can also be attributed to intraparticle swelling resulting from the alignment of water films around clays with a high charge density (Keskin, Salimi, Ateyşen, Kahraman, & Vakili, 2023). Clay particles are predominantly flat and carry an electrical charge, often negative. This significant charge concentration on the surface of the clay particles causes bipolar water molecules to be attracted to them.

Expansive soils are predominantly composed of clay minerals, such as montmorillonite and illite, which have the propensity to adsorb water molecules and expand, and desorb water, leading to shrinkage. This characteristic behaviour results in severe damage to shallow foundations, including uneven settlements, cracking, and heave, which can compromise the structural integrity of buildings and other structures (Hakro, Kumar, Ali, *et al.,* 2022; Hakro, Kumar, Almani, Ali, Hakro, Machaček, Nitsch *et al.* 2024). Clay swelling is a widespread occurrence found in soils and sedimentary rocks, and it can cause harmful stresses when the soil undergoes wetting or drying cycles. It is crucial to recognise the factors that influence this swelling to gain insights into the process and effectively prevent potential damage (Wangler & Scherer, 2008, Wang, Xu *et al.* 2024).

Over the recent past, numerous constitutive models have been designed to characterise soil behaviour. These models draw upon concepts from plasticity, elasto-plasticity, and non-linear elasticity theory. The significance of soil models has grown substantially alongside the advancement and application of computer-based techniques like finite element and finite difference methods. These computational methods typically involve several material constants and require sophisticated laboratory tests conducted under various stress paths. Stress path testing, whether performed in the laboratory or in the field, plays a vital role in formulating the constitutive laws governing soil materials. When subjected to axial and lateral loads, different elements within the soil experience distinct paths of loading or stress. Hence, determining the parameters of the constitutive model or calibrating the model constants becomes a crucial step in modelling geotechnical problems. These parameters are derived from the observed behaviour of the soil during laboratory or field tests. The continuum approach forms the basis for the finite difference method (FDM), finite element method (FEM), and boundary element method (BEM). Among these, the FEM comprises eight fundamental steps. These steps include discretisation, selecting a displacement model, defining strain-displacement and stress-strain relationships, deriving element equations, assembling and applying boundary conditions, solving primary unknowns, computing secondary unknowns, and interpreting the results. The FEM is versatile and can handle problems with material and geometric nonlinearities, complex boundary conditions, and non-homogeneities. It involves dividing the entire region of interest into discrete elements for analysis (Hemeda, 2019, 2022).

Numerous studies have been carried out on the settlement of shallow and deep foundations using various geotechnical software, such as Plaxis 2D, Plaxis 3D, GeoStudio, and others (Agraine, Bouali, & Messameh, 2020; Anand, Acharyya, & Dey; Anaokar & Mhaiskar, 2019; Byrne *et al.,* 2004; Chatra, Dodagoudar, & Maji, 2017; Dashti & Bray, 2013; Deb & Pal, 2021; Dias & Grippon, 2017; Enkhtur, Nguyen, Kim, & Kim, 2013). However, there is a limited body of research focusing specifically on foundations under expansive soil conditions. The numerical modelling of (Al-Busoda & Abbas, 2018) study examines pipelines supported on expansive soils, which are susceptible to uplift forces caused by soil swelling, leading to deformations and bending. The researchers utilized PLAXIS 3D-2013 software, employing the Hardening Soil Model for numerical modelling. They investigated different spacing configurations of helical piles to mitigate the vertical movement of pipelines resting on expansive soil. The study of (Al-Busoda & Abbas, 2017) employed numerical modelling using PLAXIS 3D-2013 software with a hardening soil model to analyse towers situated on expansive soils. Such towers experience uplift and lateral forces resulting from soil swelling and wind loads. The swelling in expansive soil further induces lateral pressure on the tower foundation, leading to deformations and bending. To mitigate the vertical and lateral movement of towers built on expansive soil, various configurations of helical piles were considered. The issue with the preceding numerical analyses conducted on various structures situated in expansive soil lies in their utilization of conventional geotechnical models like Mohr-Coulomb and hardening soil model, employing volumetric strain to represent soil swelling. Nevertheless, in practical scenarios, the swelling phenomenon is intricately linked to the water level within the soil medium. The other numerical modelling study was conducted by (El-Shamy, El-Mossallamy, Abdel-Rahman, & Ali, 2019) to calibrate the swelling rock model in Plaxis with Odometer test.

The conducted oedometer swell tests on the same soil using two techniques: the different pressure method and the huder-amberg method. They compared the results and procedures of both methods, identifying the strengths and limitations of each. As a result of this comparison, the huder-amberg method was selected for all subsequent tests due to its superior performance in determining swelling parameters. To ensure accurate and comprehensive results for the swelling parameters, they applied Grob's 1d swelling law to the experimental data. Furthermore, they developed a new user-defined swelling constitutive model in the finite element software Plaxis to simulate swelling soil behaviour numerically. The model's suitability was verified through numerical simulations based on one of the huder-amberg oedometer tests using Plaxis software's oedometer soil test facility.

Expansive ground is identified by evaluating factors such as moisture levels, swell potential, Atterberg Limits, and suction capacity of the expansive material (Fityus, Smith, Allman, & Engineering, 2004, Johnson & Snethen, 1978, Mofiz & Islam, 2010). The assessment of uplift movements in expansive soil/rock is a highly intricate hydro-mechanical problem (Marino *et al.,* 2017). The swelling and consolidation settlements within shale formations result in structural issues, such as the development of cracks and significant settlement in buildings. In Jamshoro numerous structures constructed on shallow foundations situated on expansive shale soil, leading to extensive cracks and settlement due to the uplift of these shallow foundations. Unfortunately, no study has been conducted at the Jamshoro site, where the majority of the shallow soil layers consist of expansive shale. In this study the numerical modelling using PLAXIS 2D will be employed to investigate the behaviour of shallow foundations built on expansive shale layers. The modelling will incorporate a user-defined Swelling Rock Constitutive Model, specially designed for this analysis. This study comprises of field investigation, laboratory testing, validation of model with small scale physical model and numerical simulations of shallow foundation under different cycles of dry-wet and wet-dry condition. This study will be helpful the geotechnical engineer to better design the shallow foundation under expansive soil considering wet and dry cycles.

2.0 RESEARCH METHODOLOGY

In this study the numerical modelling was performed with FEM geotechnical software Plaxis 2D to assess the heaving and settlement of foundation under different loading and wet and dry cycles. Initially the laboratory testing was performed to determine the model parameters. The swelling rock model was used for simulating the settlement and swelling response of expansive soil under dry and wet conditions. The constitutive model for swelling rock relies on the time-dependent swelling behaviour of the rock. Initially developed by Professor Thomas Benz of NTNU, the model was later enhanced by Bert Schädlich of Tugraz for PLAXIS 2D. This swelling rock model draws from the research of Anagnostou (1993) and Heidkamp & Katz (2002), encompassing stress and time-dependent aspects of swelling deformation.

The provided paper utilized a finite element numerical simulation through Plaxis software, a two-dimensional analysis tool designed for assessing stability, deformation, subsidence, compaction, and leakage under both static and dynamic scenarios within the geotechnical field (Tsegaye, 2010). To ensure an accurate representation of the factors influencing the mass, this research work incorporated numerous parameters relevant to soil swelling susceptibility analysis into the model. Consequently, the model's development and execution encompassed four key phases: establishing the geometric mass configuration, defining boundary conditions, allocating material properties and behavioural models, and conducting mechanical analysis considering saturated shale conditions. The model parameters were 100 x 10 meters in model dimensions have been so selected that the deformation in the soil does not intersect the model's boundaries.

The geotechnical parameters of soil and model parameters are mentioned in Table 1. The working conditions of Plaxis 2D software are described as follows. Plaxis 2D: The finite element analysis was conducted using Plaxis 2D version 21.2. The primary objective of the study was to numerically replicate the soil behaviour of the Jamshoro Shale sample under conditions of plain strain. This was achieved by implementing the elastoplastic Mohr-Coulomb model and a specialized swelling rock model. The analysis was specifically designed to represent drained state conditions. The foundational structure's base was modelled using a standard linear elastic material. Lateral constraints were applied along the axis of symmetry, and appropriate vertical boundaries were imposed, while the bottom boundary was confined both horizontally and vertically to mimic real-world conditions more accurately.

Notably, both the rock and soil exhibited highly nonlinear behaviour when subjected to loading conditions. The line loads on the footing were derived from distributed loads, and the phased construction technique allowed for sequential activation of the footing after applying the line load. The model geometry was effectively partitioned into components to generate a mesh, with a medium-sized mesh chosen to strike a balance between precision and computational efficiency. Thorough consideration of the model proportions ensured that direct contact between ground deformation and model boundaries was avoided. The soil model was characterized by dimensions of 20 meters in width and 10 meters in depth. To ensure successful simulations, the initial stresses were specified using either the "K0-procedure" or "Gravity loading" options, with the K0 approach being the recommended choice for horizontal surfaces. Incorporating the "standard fixity" criterion, the numerical model constrained the bottom edge to prevent vertical and horizontal movement, while the vertical edges were subjected to horizontal fixity, preserving the unchanged condition of the bottom edge.

Table 1: Model parameters
(UDSM - Swelling Rock Model Manual)

Symbol	Unit	Values
$c*$	kN/m^2	22
ψ	°	0
σ_{tens}	kN/m^2	0.001 (assumed)
E_i	kN/m^2	24711
E_p	kN/m^2	24711
v_{pt}	--	0.3
v_{tt}	--	0.3
G_{pt}	kN/m^2	....
A_0	1/day	0.033
A_{el}	1/day	---
A_{pl}	1/day	-
K_{qp}	--	10%
K_{qt}	--	10%
σ_{qop}	kN/m^2	100
σ_{qot}	kN/m^2	100
Swell_ID	--	3
Water	--	1

3.0 RESULTS AND DISCUSSION

From the laboratory investigation it was observed that the Jamshoro soil consist of shale having higher values of Atterberg's limits i.e., liquid limit of 80 % and plastic limit of 35 % and PI as 45. According to AASHTO and Unified Soil Classification System (USCS) the soil classified as A-7-5 and CH respectively. The free swell index (FSI) was 120 % and swelling pressure was 100 kPa. According to the laboratory test results, which include liquid limit, plastic limit, Free Swelling, and Swelling Pressure tests on the soil, it has been observed that the structure's shallow foundation is prone to significant expansion-related heaving, settlement caused by shrinkage, and consolidation settlements under varying structural pressures. The sieve analysis of soil is given in Figure 1. The result of sieve analysis align with Atterberg's and indicating the soil as clayey soil with large swelling potential.

The User Defined Soil Model (UDSM) Swelling Rock Model was used in Plaxis 2D to specifically capture the swelling strains due to hydration, which cannot be reproduced accurately by conventional soil models. It was successfully used in past research to model swelling pressure, heave, and stress redistribution (Al-Maamori, El Naggar et al. 2018) and is therefore a good option for expansive soils and weak rocks. Calibration was performed in accordance with the Huder–Amberg Oedometer procedure, loading soil initially in dry conditions and later under saturated conditions to monitor swelling (Plaxis Manual, 2018). The Plaxis 2D deformation curve best simulated laboratory measurements, ensuring that the employed model is a fair representation for simulating the swelling characteristics of the tested soil as shown in Figure 2.

By following the outlined steps of the modelling process described in the previous section, the mechanical stages are sequentially implemented. The step model is then computed and executed to analyse the deformations, displacements, and stress-strain behaviour under the influence of expansive soil loading. To explore the fundamental behaviour of shallow foundations on shale layers during loading, unloading, and full saturation, a series of models were created and examined. The study involved subjecting the foundation to a pressure of 100 kPa on the shale soil, followed by complete unloading to 0 kPa. Subsequently, the model was fully saturated to a degree of saturation of 100%, as illustrated in the Figure 3. The results of the model, as shown in Figure 3, indicate that the foundation settled, moving vertically downward by 15 mm at the centre of its centroid when subjected to a 100 kPa load. Upon unloading the foundation to zero pressure, it moved upward by 12 mm. After applying full saturation, the foundation experienced further upward movement or heaving of 8 mm, attributed to the expansion of the swelling shale. The concept that when expansive soils absorb water, they undergo volume expansion due to swelling mechanisms. This expansion generates internal stresses within the soil mass. It's important to understand that this is a simplified representation of the complex physical and chemical processes occurring at the microstructural level during soil swelling (Alonso, Vaunat, & Gens, 1999; Fredlund, Rahardjo, & Fredlund, 2013; Nelson & Miller, 1997).

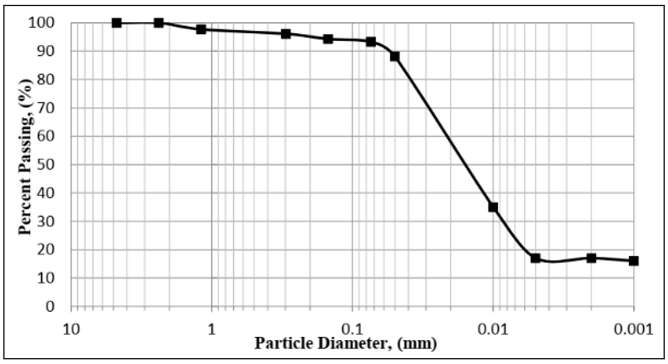

Figure 1: Sieve analysis curve

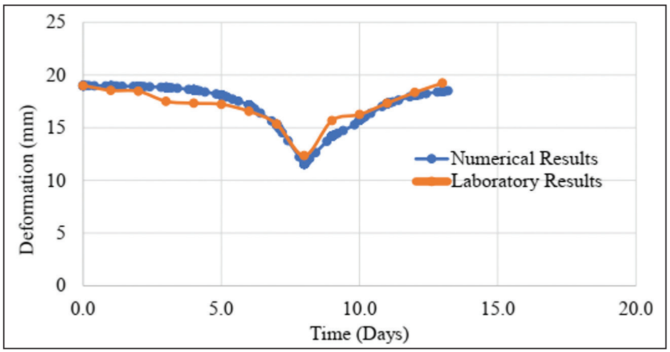

Figure 2: Calibration of swelling rock model

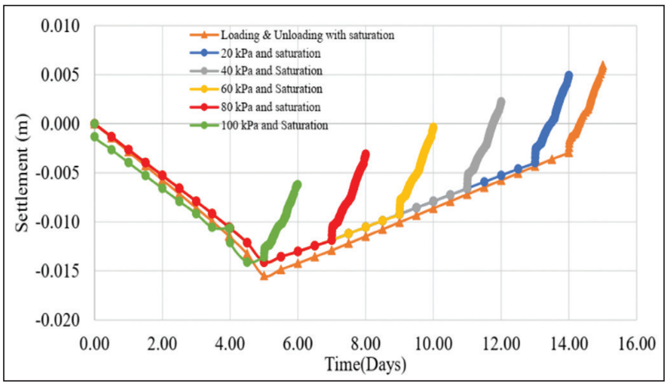

Figure 3: Loading-unloading and saturation of soil

The study investigated the behaviour of a foundation on shale soil subjected to different loading and saturation conditions. The foundation pressure was varied from 100 kPa to 20, 40, 60, and 80 kPa, and the degree of saturation was set to 100% at each loading condition. The results showed that under a foundation pressure of 100 kPa, the foundation settled by 15 mm at its centre. When the pressure was reduced to 20 kPa, the foundation moved upward by 11 mm. Upon full saturation, the foundation further heaved upward by 9 mm due to the expansion of the swelling shale.

Similarly, for foundation pressures of 40, 60, and 80 kPa, the settlement was 15 mm at the centre under the initial loading. As the pressure decreased, the foundation moved upward by 8 mm, 6 mm, and 4 mm, respectively. With full saturation, the foundation heaved upward by 9 mm in all cases. Regardless of the loading condition, when the foundation was fully saturated, it experienced upward movement (heaving) ranging from 8 to 10 mm. The initial settlement under a pressure of 100 kPa was 15 mm, which is within the acceptable limit of 25 mm for shallow foundations (Bowles 1996, (Terzaghi, Peck *et al.* 1996).

In the Figure 4, under a constant load of 100 kPa, the foundation experiences a settling of 8 mm in the absence of moisture within the shale soil. However, when the soil reaches full saturation for a prolonged period of 100 days, a substantial upward movement of the foundation by 87 mm takes place due to the swelling or heaving of the completely saturated shale soil. These findings underscore that despite the higher structural load of 100 kPa, a noteworthy vertical displacement of the foundation transpires over a reasonable 100-day span due to the swelling properties of the saturated shale. Moreover, the upward motion resulting from the expansion of the swelling shale is notably remarkable, measuring 170 mm and 150 mm for two and four-story structures respectively, when subjected to typical structural pressures of 25 kPa and 50 kPa. As moisture absorption causes expansive soil to swell, it imposes an upward pressure on the foundation, potentially leading to its elevation and thereby presenting risks to the structural soundness and overall stability of the building.

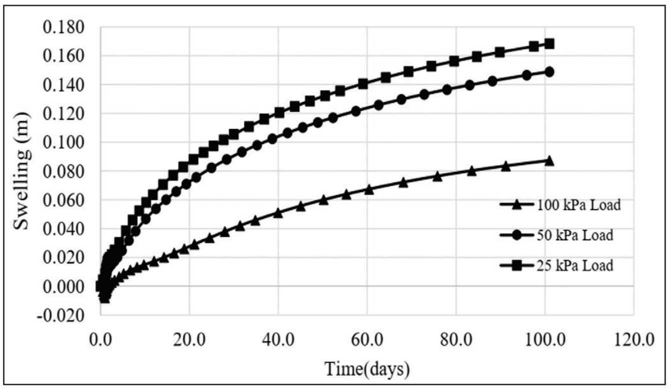

Figure 4: Behaviour of foundation at saturation under different loads

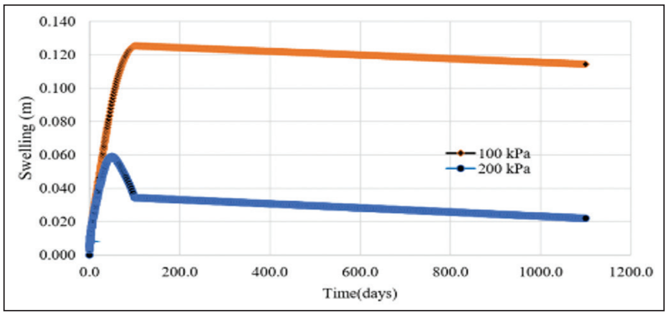

Figure 5: Saturated to dry conditions under 100 kPa and 200 kPa Load

These findings are in agreement with the research by (Khennouf and Baheddi, 2020), who indicated more than 130 mm heave at a 100 kPa load in their FLAC 3D simulations of shallow foundations on fully saturated expansive clay in N'Gaous, Algeria. Their results confirm that substantial uplift—anywhere from 130 mm to 148 mm—can happen even under moderate loads, thus validating swelling-induced foundation movement as proposed in this research.

This set of model simulations commenced by fully saturating the soil and subsequently subjecting it to a gradual drying process marked by increasing suction levels, all while maintaining constant pressures of 100 kPa and 200 kPa. The outcomes, visually portrayed in Figure 5, provide compelling insights. At a structural pressure of 100 kPa, a load equivalent to the standard magnitude experienced by a 10-story building, the foundational structure displays minimal, practically negligible, movement. This observation underscores the resilience of the foundation under this common structural load.

However, the dynamics change notably when the load is intensified to 200 kPa, effectively doubling the pressure. Under this escalated pressure scenario, a substantial settlement of 30 mm ensues. This settlement is primarily attributed to the process of shale shrinkage triggered by the elevated pressure. Remarkably, this substantial settlement phenomenon perseveres over an extended period, exhibiting a consistent behaviour in the long term. In essence, this series of models rigorously demonstrates the interplay between soil saturation, pressure levels, and resultant settlement. The findings emphasise that while the foundation maintains stability under typical loads, doubling the pressure can lead to substantial and persistent settlement due to the characteristic shrinkage of shale. These insights contribute to a more comprehensive understanding of the foundation's behaviour under varying conditions and serve as a valuable reference for construction and geotechnical considerations.

From these findings, it can be concluded that there is no substantial settlement of the footing at a structural pressure of 100 kPa when the soil transitions from its initial saturated state to a dry state, representing the load of a 10-story building foundation. However, if the soil becomes dry from its initial saturated conditions under a very high structural pressure of 200 kPa, representing the load of 20-story buildings, there may be significant settlement of the foundation. When the water table of the ground is raised abruptly to ground level, while maintaining a constant bearing pressure of 100 kPa over a period of 100 days, there is a significant upward movement of the foundation, reaching 75 mm. This movement is attributed to the heaving or swelling of the shale soil at full saturation. On the other hand, when the water table is gradually increased to ground level in multiple steps, while keeping the load constant for the same period of 100 days, the foundation experiences an upward movement of 25 mm due to the heaving or swelling of the shale soil.

These results demonstrate that there is substantial vertical movement of the foundation during a reasonable 100-day timeframe caused by the heaving or expansion of the swelling shale under a high structural load of 100 kPa when the water table is raised abruptly. However, this movement reduces to tolerable limits of 25 mm when the water table is elevated in multiple steps. Numerous studies primarily focused on the larger mechanical characteristics and smaller underlying mechanisms of expansive soil. Commonly, tests involving cycles of wetting and drying were conducted (Gallage & Uchimura, 2016; Tang *et al.,* 2020). The outcomes indicated a strong correlation between the larger mechanical traits and the soil's capacity to absorb and release water. Of particular significance was the decline in cohesion, internal friction angle, and shear strength of expansive soil as the number of wet-dry cycles increased (Wang, Tang, Cui, Shi, & Li, 2016) The intricate microstructure of expansive soil was responsible for both its characteristics of swelling and shrinking, as well as the weakening of its ability to hold moisture. Similar to other types of clay, the expansion and contraction process can be dissected into macro- and micro-structural components. The expansion mechanism, triggered by water absorption, centred on the creation and thickening of water films (Manca, Ferrari, & Laloui, 2016). This generated a "wedge" force among clay particles, leading to increased particle spacing and expanded pores. As a result, the ultimate strength of expansive soil is governed by the arrangement of pores within the soil.

This series of model simulations encompassed a diverse range of shallow foundation sizes, spanning from isolated footings to more extensive raft foundations. The impact of varying footing dimensions on the behavior of swelling shale under a bearing pressure of 100 kPa is depicted in Figure 6. For instance, an isolated footing measuring 2 meters, typically suited for 2-story residences, exhibited a vertical displacement of 100 mm. However, when the footing dimensions were enlarged to 4 meters, typically employed for 4-story buildings, the vertical displacement decreased to 87 mm. Similarly, when utilising a larger 8-meter footing, often employed for raft or mat foundations, the vertical movement showed a notable reduction. Subsequently, as the footing dimensions expanded further to 16 meters, the vertical movement diminished even more significantly to 22 mm.

These results highlight a clear trend: as the size of the foundation increases, the vertical movement of the footing diminishes. Eventually, this reduction reaches levels deemed tolerable for building structures. Consequently, the findings propose that opting for relatively larger isolated footings or raft foundations could offer benefits in curbing footing movements to acceptable thresholds for the overall structure's stability.

Figures 7 & 8 provide insight into the impact of altering the depth of the overlying shale layer, situated above a rigid limestone rock layer, on the foundation's movement. The simulation process encompassed two phases: initially observing settlement under dry conditions, followed by elevating the water level near the base of the foundation to observe swelling. The recorded values for swelling were as follows: 76 mm, 71 mm, 68 mm, 59 mm, 51 mm, 43 mm, and 41 mm for shale depths of 10 meters, 7 meters, 6 meters, 5 meters, 4 meters, 3 meters, 2 meters, and 1 meter, correspondingly. This analysis underscored a clear trend: as the depth of the shale layer decreased, the foundation's movement also exhibited a reduction, eventually reaching minimal values.

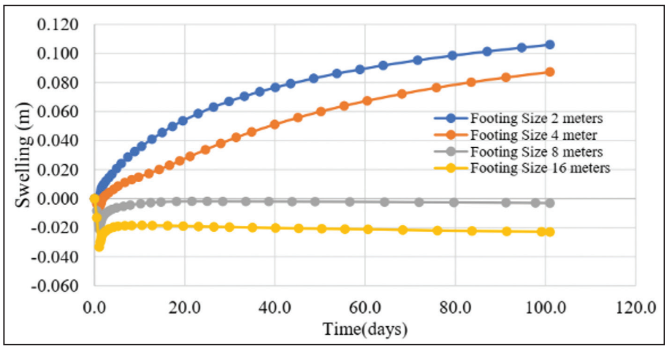

Figure 6: Footing size and heaving of footing

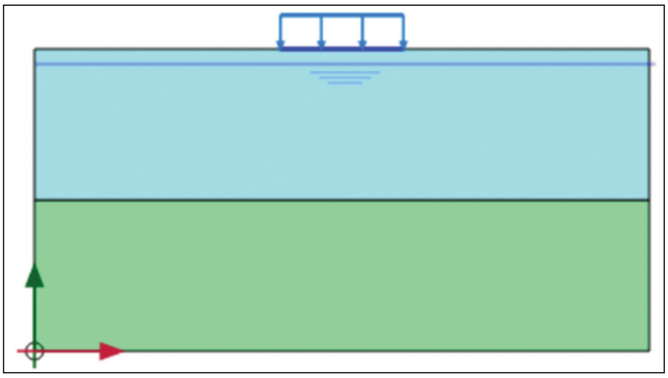

Figure 7: Effect of limestone below shale layer

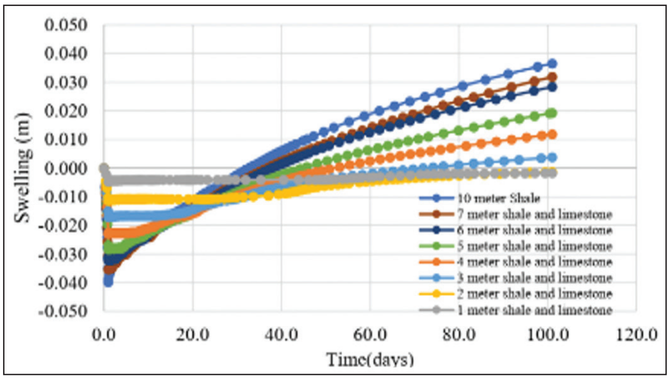

Figure 8: Effect of limestone below shale layer on swelling

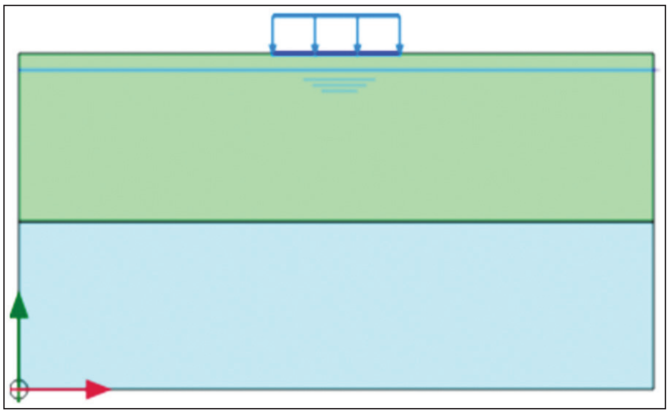

Figure 9: Shale layer below limestone

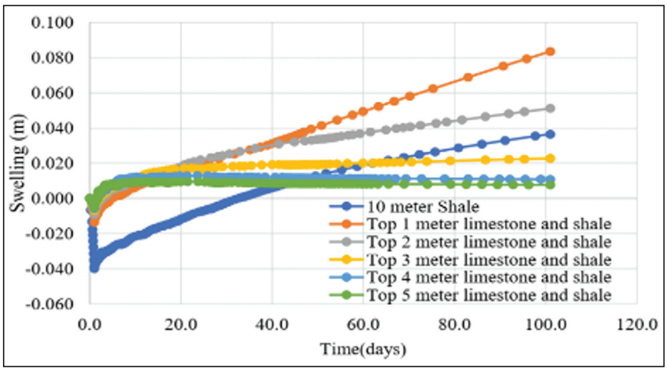

Figure 10: Swelling of shale below limestone

Figures 9 and 10 further delve into the influence of the depth of the limestone rock layer beneath the shale on the foundation's movement. The simulations followed a similar pattern, observing settlement under dry conditions and subsequently triggering swelling by raising the water level near the foundation's base. The vertical upward movement of the foundation displayed distinct variations. For instance, a 1-meter top layer of limestone rock resulted in a substantial 93 mm of vertical heaving movement, while a 2-meter limestone layer yielded 51 mm of movement. With the shale layer extending to its full depth, the movement decreased to 36 mm.

Notably, as the depth of the limestone layer increased, the swelling effect diminished, reaching a mere 7 mm with a 5-meter limestone layer. Interestingly, for limestone layers measuring 1 to 2 meters, the footing movement resembled that of a full-depth shale layer. Nevertheless, with thicker and more rigid limestone layers, the swelling potential of the soil diminished, leading to a significant reduction in the vertical foundation movement. The collective findings of this study culminate in a compelling conclusion: the strategic incorporation of an appropriate thickness of surface limestone layer can effectively mitigate the vertical movement caused by swelling. Such a layer can substantially diminish the movement to an almost negligible extent. This understanding offers valuable insights for construction practices aimed at minimising the detrimental effects of swelling on foundation stability.

4.0 CONCLUSION

The core aim of this research study was to comprehensively investigate how shallow foundations, situated on expansive soil, respond when exposed to a range of wet and dry cycles. This inquiry was conducted through the application of the Finite Element Method (FEM) Plaxis 2D software. The research unfolded in three main phases: i) Investigation and testing in both laboratory and field settings, and ii) Numerical Modelling using Plaxis 2D. The initial phase revolved around characterising the expansive soil profiles present at the research site. This involved extracting soil samples via rotary drilling and subsequently determining relevant soil parameters through laboratory examinations. The precision of these parameters was ensured via calibration. The second phase delved into numerical modelling, employing Plaxis 2D in tandem with the Swelling rock soil model, which facilitated a comprehensive analysis of foundation behaviour across diverse soil conditions.

4.1 Key Insights

- Subsurface analysis revealed cohesive deposits with considerable potential for volume change. The soil composition encompassed assorted expansive layers at varying depths, categorised as A-7-5 and CH according to the AASHTO and USCS classification systems respectively.
- Weathered and fissured limestone, along with shale layers, were identified at different depths within the research area.
- The soil in question was identified as swelling shale, characterised by a significant plasticity index and notable activity. This was predominantly attributed to the presence of active clay minerals such as Montmorillonite. The expansive nature of the soil manifested through pronounced swelling pressure and substantial potential for expansion.
- A subsequent series of model studies targeted the transient behaviour of shallow foundations situated on shale layers, considering conditions involving loading, unloading, and complete saturation. These models exposed the shale soil to a foundation pressure of 100 kPa, followed by a complete reduction to 0 kPa, and eventual full saturation.
- Results revealed that the short-term upward movement or heaving of the foundation remained within allowable thresholds of 25 mm for structures, regardless of the loading conditions.
- However, over a span of 100 days, noteworthy vertical foundation movement exceeding the permissible 25 mm limit for structures was observed. This movement endured even when the structural pressure varied between low (25 kPa) and high (100 kPa) bearing pressures. The persistence of this substantial vertical movement was attributed to the prolonged swelling of the shale, even during near-consolidated states under foundation loads or during unloading.
- Additionally, within a reasonable timeframe of 100 days, significant vertical foundation movement occurred due to the expansion of the swelling shale, particularly when the water table experienced rapid elevation. However, this movement subsided to permissible levels when the water table was gradually raised.
- These observations underscore the critical necessity of factoring in both short-term and long-term consequences of shallow foundations resting on swelling shale. Managing fluctuations in the water table emerges as a pivotal determinant in curbing vertical foundation movement, thus safeguarding structural stability and integrity.
- In conclusion, this study serves to advance the comprehension of how shallow foundations respond when placed on swelling shale, emphasising the importance of meticulous evaluation encompassing diverse conditions. This comprehensive assessment guides the development of effective strategies to mitigate potential risks and optimise structural performance.

4.2 Limitations of Work

The current study is based on the numerical modelling of shallow foundation of expansive soil of Jamshoro, therefore conclusions cannot be applied to other geographical locations or other expansive soils. ■

AUTHORS' CONTRIBUTIONS

Muhammad Rehan Hakro	Conceptualisation, study design, Writing review, editing, Data collection, methodology, and formal analysis.
Mohammad Ahsan Channa	Data validation, visualisation, and software software implementation.
Imtiaz Ali Hakro	Literature review, supervision, software implementation.

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PROFILES

MUHAMMAD REHAN HAKRO is Assistant Professor at Mehran University of Engineering & Technology Sindh Pakistan. He has extensive academic and research background in Geotechnical Engg. and Soil Mechanics. He has authored numerous research papers on various subjects and has publications in various impact factor journals. His research interests encompass Soil Mechanics, Foundation. His research interests include soil behavior, foundation engineering, and advanced geotechnical analysis. Dr. Hakro is expert in Finite Element analysis with geotechnical software such as Plaxis and Geo-studio.
Email address: Rehan.hakro@faculty.muet.edu.pk

MOHAMMAD AHSAN CHANNA is currently working at Sindh Agriculture University, Tandojam, as an engineer. He has very strong technical skills in the field of soil mechanics and structural engineering. His B.E. and M.E. work was related to soil stabilization, and his contributions to the field have created published papers in recognized journals. His current research interests include ground improvement and sustainable geotechnics.
Email address: ahsanchanna28@gmail.com

IMTIAZ ALI HAKRO has a background in Petroleum Engineering and significant research experience and knowledge in the petroleum domain. He remains actively engaged in various operations and research work connected to Engineering, Petroleum Exploration, and Production, and his technical skills include research-based problem-solving in the Energy domain.
Email address: imtiazhakro@yahoo.com