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PREDICTION OF THE BEARING CAPACITY AND BEHAVIOR OF MONITORED SOFT SOIL EMBANKMENT FOUNDATIONS

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ПРОГНОЗ НЕСУЧОЇ ЗДАТНОСТІ ТА РЕЖИМУ НАВАНТАЖЕННЯ ОСНОВ ФУНДАМЕНТІВ ІЗ М'ЯКОГО ГРУНТУ НА БАЗІ МОНИТОРИНГУ

Purpose. This research aims to identify and analyse the bearing capacity and subsidence of a monitored embankment clay foundation through the data exploitation of the *in situ* monitoring results (settlement plates). The results are then compared to the theoretical calculations used the pressure-meter test toward evaluating its reliability. Thus, the present research highlights the importance of understanding the method of bearing capacity evaluation as well as the recent orientation towards numerical simulation by finite element method using software PLAXIS 8.2 to evaluate the stability and to perform a more realistic analysis of the soft soil foundation behaviour beneath embankments.

Methodology. The analysis is based on the *in situ* monitored by the settlement plates with different depths to understand the real behaviour of the foundation under loading, and the exploitation of the geotechnical investigation by pressure-meter test. The loading programme and numerical modelling via finite element method was also used.

Findings. Major experimental results and findings were related to the role of the *in situ* monitored used in this analysis and the conformity of the results between the different techniques for the bearing capacity evaluation. In addition, the loading program of the embankment and the curve of loading with settlement have shown to affect the best understanding of the bearing capacity analyses.

Originality. This variety of techniques helps us to understand the foundation behaviours under loading. The ability of the pressure-meter tests and the numerical modelling via finite element method to identify the bearing capacity in these conditions was evaluated, and can be generalized to the remaining zones that are closer and that share the same geotechnical characteristics. To better understand the feasibility and the reliability of each technique of the bearing capacity evaluation, the results were confronted to the real behaviour (instrumentation) through the exploitation of the loading programme data.

Practical value. The instrumentation results can be useful as a database for the behaviours models validation, as well as theoretical technique for the bearing capacity evaluation. The results of monitoring obtained can also be generalized to the other zones that share the same geotechnical characteristics. The importance of the loading programs effects the staged construction technique presented in the results of the analysis can also be exploited.

Keywords: *bearing capacity, clay foundation, monitoring, numerical modelling, pressure-meter test*

Introduction. The conception and the realization of buildings in difficult geological and geotechnical conditions, with the low bearing capacity of the foundation beneath the construction poses the problem of the soil's ability to safely carry the pressure placed on it. In effect, this is due to the Engineered Structure which usually causes shear failure with accompanying large settlements. Thus, the most famous bearing capacity failures in history are: the Transcona Grain Elevator (1913), Tower of Pisa (1838), Venetian Bell Towers (1851), Tschebotarioff (1951), and many others. The behaviour of the ground, or more precisely its deformations under the constraints and its resistance to the transmitted loads, depends appreciably on physical and mechanics proprieties of soil, which in turn explains the study importance of these proprieties within the framework of a construction project.

The evaluation of the representative geotechnical characteristics is an important phase in this task which requires a particular precaution that is linked to the different sources of uncertainty. The latter include: the selection, the inevitable measurement errors, mathematical models imperfection, and also the variability of time and place of the geotechnical Parameters, Magnan *et al*. 1999 cited bay Zibani. (2012) [1], Al Hussein, M. (2001) [2], Atkinson. (2007) [3].

The *in situ* tests are an operation that can reduce the source of uncertainty and can also manifest the site heterogeneity. In addition, the economic factor and the time frame of the realization is short; Gambin, (1995) [4], Moreover, the pressure-meter tests gauge is used as preferential tool Combarieu, (1997) [5].

The article exposes a factual case of some difficult conditions that appeared in the clay plain, which represents an important part of the Algerian East-west Highway. The latter was affected by a rupture caused by the embankment loading. The rupture passes through different field zones characterised by wet and flood conditions in addition to the clay foundation, these adverse conditions pose a particularly difficult challenge to the National Highway Agency.

Connection of work for the sake of the previous studies. The rupture problem of the embankment built in soft ground foundation attracts the attention of the research centres of many countries, so as to predict the behaviour of these buildings and especially the optimal dimensions without rupture namely by (Rankine., 1857; Terzaghi., 1943; Taylor., 1948, Favre, 1995); cited in [1] and then follows research undertaken by Combarieu (1997) [5] Atkinson. (2007) [3] and many authors.

The difficulty of the behaviour's forecast mentioned previously paved the way towards of the embankment instrumentation during the construction so that we understand the real behaviour of embankment and its foundation such as Adel Aissi et all (2013) [6] Gavan Hunter and al,(2003) [7].

In this study the section of embankment foundation was monitored by settlement plates with different depths Hence, this research aims to identify and analyse the Bearing capacity and settlement of the different zones through the data exploitation of the *in situ* measurement results (settlement plates), then the results are compared to the theoretical calculations by the exploitation of the pressure-meter test toward evaluating its reliability. Finally, the present research highlights the importance of understanding the bearing capacity and the rupture mechanisms of the foundations with the recent orientation towards the numerical simulation by finite element method using PLAXIS software 8.2 to evaluate the stability to perform a more realistic analysis of the behaviour of soft soil foundation beneath embankments as shown by: Chai & Bergado (1993) [8].

All these techniques used to evaluate the bearing capacity promise reliable results and show the different factors which lead to the concord of different techniques. Furthermore, this variety of techniques helps in understanding the foundation behaviours under loading condition and leads us to generalize the findings to other zones that are closer and that share the same geotechnical characteristics.

Situation: Geotechnical and Geological Context of Boutheldja Plain. ***Site Description.*** Botheldja city located 45 Kilometres from the Wilaya of Annaba in Eastern Algeria. The basin of Boutheldja stretches over an area of about 2 acres. This zone didn't witness urban development before due to its complexity, its low bearing capacity, its high compressibility, as well as its flooding danger. In all these conditions, the embankment of the East-west Algerian Highway crossed. This embankment is affected by the failure which caused so much damage and cost. The site was subjected to intensive investigation represented by *in situ* tests: (penetration tests (SPT) performed in accordance with the NF P94-116 standard, a Menard-type pressure-meter and in accordance with NF P94-110 standard), as well as laboratory tests: physical and mechanical. The position of in situ investigations is presented on (Fig. 1).

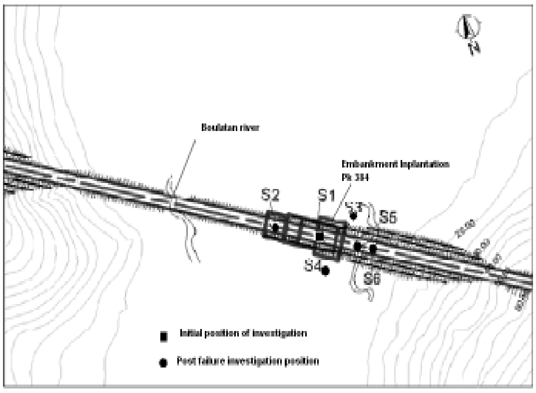

Fig. 1. Plan View of Site Investigation positions of pressure meter test

Both in situ tests and laboratory tests were carried out by the Geotechnical laboratory Fonda soil, 2007, Public Works Laboratory – direction of Constantine, and COJAAL soil Laboratory, and completed by further investigation in 2009 after the failure of the embankment infrastructure [9].

This investigation shows the different parts of the foundation. As a result, the subsurface geological data on the site reveal the existence of four main soil layers with variable thickness. An accumulation of clay (CL) layers is found from the surface up to a depth of 23 m. which is followed directly by a four-meter thick layer of Organic clay (OC), The last five meters of this clay layers include a small layer of deteriorated quality of sand (GS), which is followed directly by a four-meter thick layer of sand. The substratum is composed of sand and gravel, which extend to a depth of 35–50 meters.

The results of the geotechnical investigation by *in situ* tests using pressure-meter test of deferent survey are shown in (Tab.1).

Table 1

The *in Situ* Pressure-Meter Test Results

	Pressure Limit(bar)				Pressure metric module(bar)			
depth (m)	S1	S2	S3	S4	S1	S2	S3	S4
3	5.5	2.99	3.5	2.8	51	14.55	0.9	19
6	5.2	2.52	1.7	1.3	56	17.99	1	6
9	5.,4	6.74	3.2	1.8	59	37.95	0.9	34
12	5.2	3.07	4.4	2.4	63	26.45	2.7	21
15	7.7	3.99	5.1		81	9.53	1.4	
18	7.,3	1.61	5.8	8.8	77	5.64	2.6	46
21	7.1	6.69	6	7	81	51.04	2.1	47
24	7.7	5.51	3.3	7.3	86	27.82	0.9	
27	27	6.72	1.8	0.9	385	35.33	0.7	48.1
30	33	83.9	45.5	81.8	505	9658	19.7	48.2
33		83.8	81.3	81.9	51	6074	47.8	48

Instrumentation Plan. The embankment foundation is monitored during the construction phase (Fig. 2) in order to understand the settlement of the embankment in detail, and to supervise the stability of embankment site.

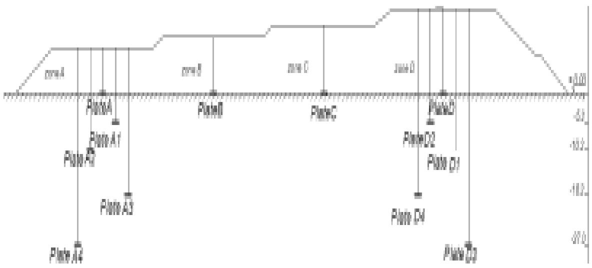

Fig. 2. Monitoring Instruments Position (long profile)

In this case, the monitored foundation becomes one of the geotechnical investigation tools. And to avoid the different sources of uncertainty for the evaluation of the stability [1], [3]. In order to simplify the behaviour analysis, the embankment body in construction is divided into four zones (A, B, C, D) according to their different heights, (i.e. four different conditions of loading). The maximal height of the embankment is 15 m with a length of 500 m and 18° slope angle.

Results and discussion. ***The Embankment foundation Behaviour.*** The material used in the embankment body is C1A3 conformed to guide earthwork road, and the direct shear test gives Cu=5KN/m2 φ=30°, the unit weight is γ=21KN/m3. Thus, the importance of the construction technique on the foundations behaviour, cited by [2], [3], [6], [8] is also considered. The embankment implementation was made by staged construction technique with 40 cm thickness and the compaction control was carried out in site by means of Troxler and plate bearing.

The evolution of settlement with time measured by the settlement plates for the zone C and D are presented in Fig. 3.

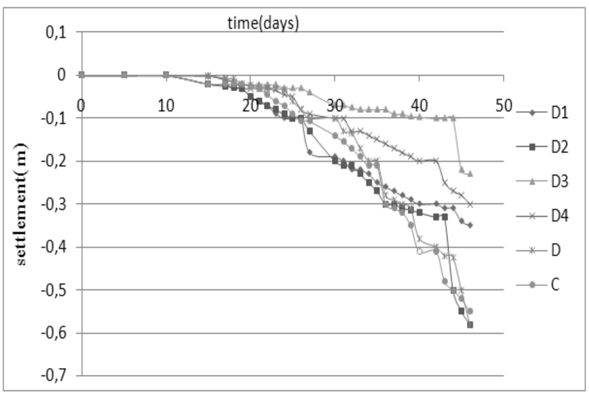

Fig. 3. Results of the vertical displacements by the settlement plate of the zone (C) and (D)

Through the analysis of the curves displacement with time, we notice the following.

At the initial construction stage, the settlements beneath the embankment are small and so is the lateral displacement. This is due to the over-consolidated state of the soil, and with the next loading, we move to the second stage of the embankment on the compressible soil life as mentioned by; [6], [7] the subsoil becomes normally consolidated with an undrained behaviour, and causes an important vertical (57 cm) as well as lateral displacements. The curves of loading clearly exposed the critical height or occur the rupture of deferent lay down zone C and D (Fig. 4).

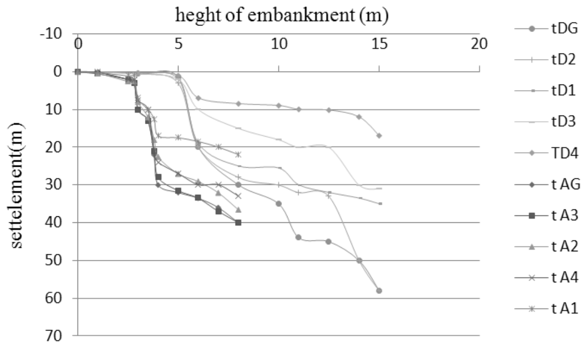

Fig. 4. Loading and deformation curve of subbase under embankment of different depths

Using the curve of loading with subsidence, we noticed that the form of failure is complex. That is, there is no instantaneous rupture presented in the curve of loading.

The critical height of loading which can be supported by the foundation called safe state where the load is about 3m (i.e. 65kpa). The movements are relatively large but the structure is still in a stable state. Whereas, increase in the embankment loading up to 5 m height, results in yielding of the foundation which is limited just underneath, with no sign of yield at surface body of the embankment.

The over-consolidation state of the surface layer foundation partially isolated the spread of the yielding process in the embankment body Moreover; the time loading program which has set ten days off has favourably results to significant increase in the foundation resistance.

Evaluation of bearing capacity by the pressure-meter test. The pressure-meter test is used to evaluate the bearing capacity of the different zones. This technique was highlighted by [3], [4]. The formula of Combarieu [5] is exploited and then compared to the *in situ* measurement results.

The ultimate limit state q_u is the intensity of bearing pressure at which the supporting ground is expected to fail in shear, i.e. a building will collapse

$$q_u = 0{,}9 \cdot P_{le}. \quad (1)$$

The Safe bearing capacity where the movements are relatively large but the structure has not collapsed

$$q_s = \frac{q_u}{F}, \quad (2)$$

where F = factor of safety (normally 3.0).

The results show that for the zones;

D, q_s = 78.75 kpa;

C, q_s = 112.5 kpa;

B, q_s = 90 kpa;

A, q_s = 76.5 kpa.

The following graph (Fig. 5) shows the bearing capacity of the zones through the exploitation of the Pressure-meter test.

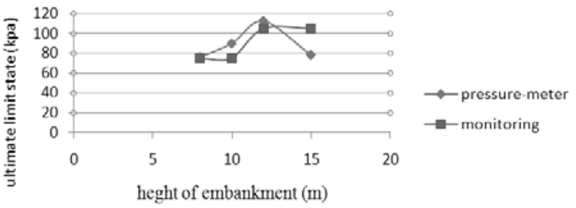

Fig. 5. Ultimate limit state of the zones through the exploitation of the pressure-meter test

The evaluation of the bearing capacity of different zones by the pressure-meter test exploitation and the real condition on ground give similar results. The simple difference between both kinds of results can be: the site of the surveys of this zone. In fact, these results are different from the results taken from the site of the settlement plates position. In addition, the different sources of uncertainty quoted previously. The rupture occurs at the time of going beyond the height of 5m taken by the measurement on ground. On the other hand, it reaches 6m for calculation with pressure-metre.

Numerical Modelling of Stability. Numerical finite element techniques are widely used for the solving geotechnical problems. Such techniques are favoured especially for the stratified grounds (SN) and complex condition where the traditional methods of equilibrium ultimate and of limiting analysis prove to be inefficient. Thus, the numerical program along with the progress of modelling and their exactitude based on the models advanced, the digital technique applied and the quality of data necessary are best exploited. Therefore, the engineer must choose the best model adapted to the problem that he wishes to treat according to the conditions met *in situ*.

The choice of the behaviour model depends in fact on the problem arising: supporting, Embankment settlement, foundation on inclined ground, tunnel i. e. which model of behaviour to use for which geotechnical problem [2]. Mohr- Coulomb (MC) model used for the sand and Colluvium materials (CO) also The Soft Soli Model (SSM), (Brinkgreve, 1994): it is about an elastoplastic model with hardening, the soft soil model proves to be able to predict the behaviour of the short-term foundation thanks to its simplicity and its wide use. [6], YIN Zhen-yu, (2009) [10], Jinchun Chai, 2012 [11] (Tab. 2). below provides the different parameters of the model used in the simulation of embankment (Em) and its foundation.

Geotechnical Characteristic of Site for Modelling. *Grid and Boundary Condition*. The 60-meter foundation under the embankment was modelled by 6 layers **(**Fig. 6).

The foundation was with a grid of 150 m length and 60 m height (geometrical fig. model of project.) because one finds with this depth of materials to the sufficiently strong deformation modulus of to regard as in deformation. The studied problem illustrated where one distinguishes the different zones composing the foundation.

Table 2

Parameters for Soil Used in Numerical Analysis

SN	Depth (m)	model	*e0*	φ°	*Kv* (m/s)	Cc	C_u (kpa)	K0
CL	18.5	SSM	1.64	16	$1.9\cdot10^{6}$	0.,246	41	0.72
OC	2.5	SSM	1.97	13	$2.3\cdot10^{6}$	0.471	17	0.77
GS	1	M C	0.7	13	$1.8\cdot10^{5}$	0.359	17.8	0.77
OC	2	SSM	1.97	13	$2.3\cdot10^{6}$	0.55	17	0.77
GS	4	M C	0.7	13	10^{-5}	0.344	17.8	0.77
CO	10	M C	0.5	30	10^{-5}	0.096	25	0.5
CO	30	M C	0.7	35	10^{-5}	0.096	40	0.5
Em	15	M C	0.81	25	10^{-4}	-	5	-

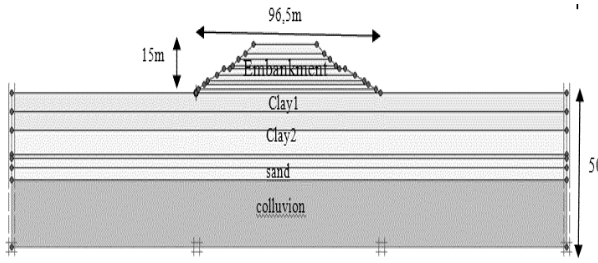

Fig. 6. Problem Geometry

The mesh and boundary conditions used for finite element analysis are shown below. (Fig. 7).

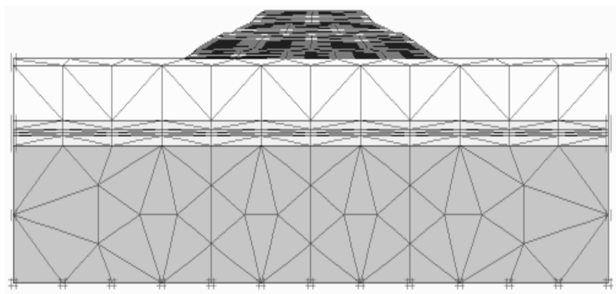

Fig. 7. Grid and Boundary Conditions of the Problem

Calculations. The progressive construction stage was modelled by 8 layers of soil spreading corresponding to 43 days of the practical work calendar. The boundary conditions taken into account in these calculations are the following:

Drainage is set from the upper part of the first layer; the initial state is characterized by a hydrostatic distribution of the pore water pressure, with an original table on the level - 10m of ground.

The primary consolidation responsibility for the which occurs during the development of present project (implantation phases) makes it possible for us to make a modelling with the soft soil model (SSM) for the clays layer then, the exploitation of the staged construction option found in the code Plaxis.

In the process of loading, the activation of a element layer is the optimal solution to take into account the staged construction (Chai and Bergado, 1993), because the modelling results and their exactitude depends on the behaviour law and also the digital technique used, thus after the constraints initialization by K0. Calculation is carried out in two stages corresponding respectively to the layered construction and to the ground consolidation under loadings.

The embankment construction was modelled by the activation of the embankment sleep after layer in a way to follow the calendar of embankment construction then for each phase of loading. It is necessary to take into account the consolidation time if there exists according to the real calendar of execution.

Phi/C reduction for the factor of safety calculation, Phi-C reduction is an option available in PLAXIS to compute safety factors, In the Phi-C reduction approach the strength parameters tan φ and C of the soil are successively reduced until failure of the structure occurs.

The total multiplier

$$\sum MSF = \frac{\tan\varphi_{input}}{\tan\varphi_{reduced}} = \frac{c_{input}}{c_{reduced}}, \qquad (3)$$

where the strength parameters with the subscript 'input' refer to the properties entered in the material sets and parameters with the subscript ‘reduced’ refer to the reduced values used in the analysis. MSf is set to 1.0 at the start of a calculation to set all material strengths to their unreduced values.

Modelling results. The Results obtained from have show to be a powerful tool for predicting the behaviour of embankment under progressive construction, the numerical analysis gives results which are in good correlation with that observed in-situ. The factor of safety calculation with the method phi/c reduction gives satisfying results, where the factor of safety is weak (Fs≈1) in the early stage of loading (Fig. 8). And become 0.8 in the stage 7 i-e in the 6 m of embankment high, the calculations stopped in phase 07 and marked collapse roughly of real behaviour on cite concluded by *in situ* instrumentation.

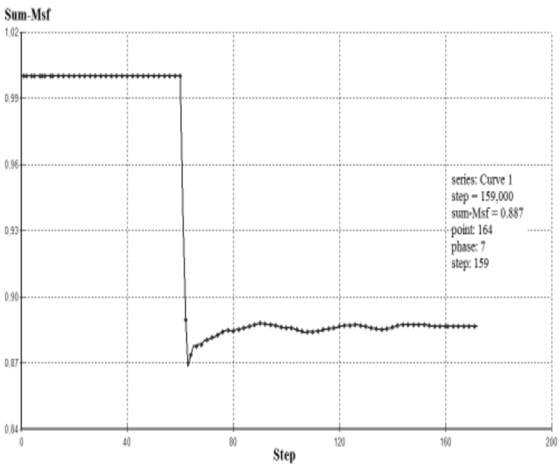

Fig. 8. Factor of Safety in Different Phases of Construction

Conclusion. The different sources of uncertainty for the prediction of the foundations behaviour under loadings and the bearing capacity evaluation pose a challenge for the geotechnical engineer. Consequently, it invites a private precaution. The variation between measurements of the foundation behaviours taken by monitored *in situ*, and the results calculated by the pressure-metre method, and also numerical modelling show the important role of the instrumentation as a crucial means for the geotechnical investigation. Therefore, we should benefits from these monitoring results and generalize them to the zones having the same geotechnical characteristics. Thus, we optimise the geotechnical investigation programs.

Indeed, the analysis of the curve of loading without the assistance of the loading programme to identify the ultimate state will be so difficult. The over-consolidation state of the superior layer and the stop of loading during 10 days (between 15 and 20) avoid the cracks appearance in the embankment fig and deferred the rupture to 40 days.

The modelling technique gives results near to reality and the rupture occurs with the height of 6 m similar to the results of *in situ* instrumentation. It is for this reason that the modelling technique of articulation in the evaluation and foundation prediction of behaviour witness a wide use in the geotechnical field where the results are very sensible to the method and to the digital technique used.

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Мета. Ідентифікація та аналіз несучої здатності й осідання глинистого фундаменту шляхом дослідження результатів натурних вимірювань осідання плит.

Методика. Аналіз заснований на натурних вимірах осідання плит на різних глибинах для розуміння реальної поведінки фундаменту під дією навантаження в різних геотехнічних умовах з випробуванням тиском. Була також використана програма навантаження й чисельне моделювання за допомогою методу скінченних елементів.

Результати. Основні експериментальні результати та висновки пов'язані з роллю натурних спостережень, що використовуються при аналізі узгодженості результатів, отриманих різними методами для оцінки несучої здатності. Крім того, показано, що програма навантаження насипу й крива навантаження з розрахунками впливає на краще розуміння несучої здатності основи. Дане дослідження показує важливість методу оцінки несучої здатності, заснованого на чисельному моделюванні за допомогою методу скінченних елементів (код Plaxis 8.2), для реалістичного аналізу поведінки глинистого фундаменту під насипом.

Наукова новизна. Використане різноманіття методів допомагає зрозуміти поведінку фундаменту під навантаженням. Були оцінені можливості вимірювального тесту тиском і чисельного моделювання методом скінчених елементів для визначення несучої здатності в цих умовах, що може бути поширене на інші зони з подібними геотехнічними характеристиками. Щоб краще зрозуміти можливості й надійність кожного методу оцінки несучої здатності, результати зіставлялися з реальним режимом шляхом дослідження даних програми навантаження.

Практична значимість. Результати інструментальних вимірів можуть бути корисні в якості бази даних для верифікації моделі, а також теоретичної методики оцінки несучої здатності. Отримані результати моніторингу також можна поширити на інші зони, що подібні вивченим за геотехнічними характеристиками. Для поетапного будівництва також є важливими й можуть бути використані представлені результати аналізу програми вантаження по кривій навантаження.

Ключові слова: *несуча здатність, м'який ґрунт, моніторинг, чисельне моделювання, вимірювальний тест тиском*

Цель. Идентификация и анализ несущей способности и оседания глинистого фундамента путем исследования результатов натурных измерений оседания плит.

Методика. Анализ основан на натурных измерениях оседания плит на разных глубинах для понимания реального поведения фундамента под действием нагрузки в различных геотехнических условиях с испытанием давлением. Была также использована программа нагружения и численное моделирование с помощью метода конечных элементов.

Результаты. Основные экспериментальные результаты и выводы связаны с ролью натурных наблюдений, используемых при анализе согласованности результатов, полученных различными методами для оценки несущей способности. Кроме того, показано, что программа нагружения насыпи и кривой нагрузки с расчетами влияет на лучшее понимание несущей способности основания. Данное исследование показывает важность метода оценки несущей способности, основанного на численном моделировании с помощью метода конечных элементов (код Plaxis 8.2) для реалистического анализа поведения глинистого фундамента под насыпью.

Научная новизна. Использованное разнообразие методов помогает понять поведение фундамента под нагрузкой. Были оценены возможности измерительного теста давлением и численного моделирования методом конечных элементов для определения несущей способности в этих условиях, что может быть распространено на остальные зоны с подобными геотехническими характеристиками. Чтобы лучше понять возможности и надежность каждого метода оценки несущей способности, результаты сопоставлялись с реальным режимом путем исследования данных программы нагружения.

Практическая значимость. Результаты инструментальных измерений могут быть полезны в качестве базы данных для верификации модели, а также теоретической методики оценки несущей способности. Полученные результаты мониторинга также можно распространить на другие зоны, которые подобны изученным по геотехническим характеристикам. Для поэтапного строительства также представляют важность и могут быть использованы представленные результаты анализа программы нагружения по кривой нагрузки.

Ключевые слова: *несущая способность, мягкий грунт, мониторинг, численное моделирование, измерительный тест давлением*

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