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Comparison of settlements by geodetic methods and numerical modeling. Test case: fuel storage tank

Comparación de asentamientos por métodos geodésicos y modelado numé-rico. Caso de prueba: Tanque de almacenamiento de combustible

Comparação de assentamentos por métodos geodésicos e modelagem nu-mérica. Caso de teste: Tanque de armazenamento de combustível

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Ciencias técnicas y aplicadas
Artículo de investigación

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Abstract

This research project addresses the necessity to update the admissible values of defor-mations, set by the rules for the design of foundations, based on the comparative analysis of settlements determined by direct (geodetic) methods on conditions of field, with the vertical displacements obtained by the ¨deterministic¨ numerical modeling by the finite element method (FEM). In order to, a shallow foundation of a tank for the storage of fuel was selected as a case study. In addition, the geodetic measurements made during the water load test were taken as a reference pattern, using the high precision geometric leveling and the soft-ware SIGMA / W module of the GeoStudio 2012 was used to perform the calculation of verti-cal displacements. The comparison was carried out with respect to the absolute maximum settlement, for different time intervals and load steps; observing an acceptable correlation between the settlements measured and those calculated by numerical modeling, evidencing the feasibility of using this software for the forecast of settlements. This investigation pro-vides valuable information on the real deformations, for the control of works during the con-struction and operation processes. The results allow the improvement of the methods of cal-culation and design of foundations based on the limit state of deformation, as well as alert-ing about the operational safety of this type of work in the Cuban industry. The use of the geodesic method allows to check the software parameters and to adjust the limit values of the displacements fixed in the current regulations.

Keywords: Fuel storage tank; water load test; settlement monitoring, numerical modeling.

Resumen

Este proyecto de investigación aborda la necesidad de actualizar los valores admisibles de deformaciones, establecidos por las reglas para el diseño de cimentaciones, con base en el análisis comparativo de asentamientos determinados por métodos directos (geodésicos) en condiciones de campo, con los desplazamientos verticales obtenidos. por el modelado nu-mérico ¨determinista¨ por el método de elementos finitos (FEM). Para ello, se seleccionó co-mo estudio de caso una base poco profunda de un tanque para el almacenamiento de com-bustible. Además, se tomaron como patrón de referencia las medidas geodésicas realizadas durante la prueba de carga de agua, utilizando la nivelación geométrica de alta precisión y se utilizó el módulo de software SIGMA / W del GeoStudio 2012 para realizar el cálculo de los desplazamientos verticales. La comparación se realizó con respecto al asentamiento máximo absoluto, para diferentes intervalos de tiempo y pasos de carga; observando una correlación aceptable entre los asentamientos medidos y los calculados por modelación numérica, evidenciando la factibilidad de utilizar este software para la previsión de asen-tamientos. Esta investigación aporta valiosa información sobre las deformaciones reales, para el control de las obras durante los procesos de construcción y operación. Los resulta-dos permiten mejorar los métodos de cálculo y diseño de cimentaciones basados en el es-tado límite de deformación, así como alertar sobre la seguridad operacional de este tipo de trabajos en la industria cubana. El uso del método geodésico permite verificar los parámetros del software y ajustar los valores límite de los desplazamientos fijados en la normativa vi-gente.

Palabras clave: Tanque de almacenamiento de combustible; prueba de carga de agua; moni-toreo de asentamientos, modelado numérico.

Resumo

Este projeto de pesquisa aborda a necessidade de atualização dos valores admissíveis de deformações, estabelecidos pelas regras de projeto de fundações, com base na análise comparativa de recalques determinados por métodos diretos (geodésicos) sobre as condições de campo, com os deslocamentos verticais obtidos. pela modelagem numérica ¨determinística¨ pelo método dos elementos finitos (FEM). Para tanto, foi selecionada como estudo de caso uma fundação rasa de um tanque de armazenamento de combustível. Além disso, as medições geodésicas feitas durante o teste de carga hídrica foram tomadas como padrão de referência, utilizando o nivelamento geométrico de alta precisão e o software do módulo SIGMA / W do GeoStudio 2012 foi utilizado para realizar o cálculo dos deslocamentos verticais. A comparação foi realizada em relação ao recalque máximo absoluto, para diferentes intervalos de tempo e etapas de carregamento; observando uma correlação aceitável entre os recalques medidos e os calculados por modelagem numérica, evidenciando a viabilidade da utilização deste software para a previsão dos recalques Esta investigação fornece informações valiosas sobre as deformações reais, para o controle das obras durante os processos de construção e operação. Os resultados permitem aprimorar os métodos de cálculo e dimensionamento de fundações com base no estado limite de deformação, bem como alertar sobre a segurança operacional deste tipo de obra na indústria cubana. A utilização do método geodésico permite verificar os parâmetros do software e ajustar os valores limites dos deslocamentos fixados na regulamentação em vigor.

Palavras-chave: Tanque de armazenamento de combustível; teste de carga de água; monitoramento de assentamento, modelagem numérica.

Introduction

New technologies are currently being developed for the geometric monitoring and analysis of deformation, these are mainly based on geodetic and/or geotechnical measurements, although traditionally each discipline has shown results separately, which limits the interdisciplinary scope when making appropriate decisions while the control of works in the construction and operation processes. Therefore, in order to solve this problem, the deformation analysis has been extended to physical interpretation, incorporating the numerical methods for finite element modeling, which has allowed a better understanding among specialists and planners of other disciplines, such as: Geodesy, Geotechnics and Civil Engineering [1-3].

The continuous or spaced supervision of the structure's behavior allows to detect the vertical and horizontal displacements in the structure's body, which can be used in the verification of the constructions hypothesis and theories related to the soils mechanics and operational work safety. Due to the current insufficient data of these investigations, the observations and recording of the real-scale deformations not only are of scientific interest for the geotechnical design, but also for the numerical methods verification used in the deterministic modeling, as well as indicators of the long-term constructions behavior [4,5].

The foundations are the support for the work's stability and they are designed fixing parameters with certain limit values to resist deformations. However practice it's built in complex places and phenomena (natural and artificial) provoke a soil behavior that differs from the conditions predicted in the research and laboratory tests [6]. To prevent these deviations it is necessary to establish a monitoring program based on observations (geodetic and/or geotechnical) in field conditions, during the construction and operation processes [7].

Different standards have been used for the foundations design, which have suffered modifications since the 1980s, which include derogations. The current [8], is based on the deformation criterion for the design of superficial foundations, however, the values set for the limit deformations (absolutes and relatives) have remained unchanged. Therefore, it is necessary to carry out real scale research for the improvement of this standard. It is important to notice that current values, even though they have been accepted by most specialists, are the result of the experience of other countries, mainly from the ex-USSR [5, 9].

Some authors [1-3, 10-12] have focused their research on the comparison of the values of the deformation determined by the geometric modeling that is, by the geodetic method, with those calculated by the numerical modeling by the FEM, these research project has been carried out fundamentally in dams.

The objective of this research is to carry out a comparative analysis between the values of the settlements determined by geodetic methods (high precision leveling) and those obtained by deterministic modeling by the finite element method (FEM) using the Sigma/W module of the Geostudio 2012 software, testing the water load in a vertical tank for the storage of fuel located in the industrial area of the nickel region of the Holguin Province.

The structure consists of a vertical cylindrical tank with a storage capacity of 15,000 tons of fuel, with an external diameter of 32 m and a height of 22.5 m, finished by a steel vault. Fig. 1.

Figure 1: Fuel storage tank.

Materials and methods

It is necessary the dimensional and non-destructive inspection with the use of geodetic and/or geotechnical methods in the storage tanks during the construction and operation processes. The main parameter to be observed while the monitoring are the settlements, where the geodetic measurements constitute a pattern for the comparison of the rest of the methods [5,13].

In the present investigation, the authors make a comparison between the settlements determined by the geodetic method from the results of the measurements in field conditions, with respect to the values calculated from the numerical modeling by the FEM with the Sigma/W module of the GeoStudio 2012 software. For this, the test of the water load of a fuel tank was taken as a case study.

Settlement inspection in storage tanks

Storage tanks are the set of enclosures and containers that contain or may contain toxic, combustible and flammable liquids and are present in most industries. For this reason, according to [13] its construction is not conceived without rigorous inspection program. Also [14] refers that within the general inspection, the study of verticality, roundness, settlement and thickness of the plates that make up the body, the bottom and the roof of the tank must be taken under consideration. To determine the effects of settlement on storage tanks, it is common to monitor control points located at the base of the foundation. In most cases, the monitoring program starts with construction and continues during the operations, making measurements with a planned frequency, based on predictions of soil settlement. For tanks that do not have initial information, the monitoring program should be based on the history prior to service [10].

Storage tanks are relatively flexible structures and they can tolerate larger settlements than other engineering works. However, according to [13, 15] there is a limit for the settlement expected to be estimated in the design with some security.

The absolute settlement can be predicted from the geotechnical soils tests and by numerical methods (statistical and deterministic). This does not generate additional forces in the structure because their behavior is uniform, however, when forces are excessive they can affect the interconnections (pipes, nozzles), generating unforeseen forces in the design. According to [5], the Average absolute settlement (Sc) is calculated by the following expression:

$$\overline{S_c} = \frac{\sum_{i=1}^{n}(A_i.S_{CAi})}{\sum_{i=1}^{n}(A_i)} \qquad (1)$$

where:

S_{CAi}: absolute foundation settlement (i),

A_i:foundation area (i) and

n: total foundation amount of the work.

Differential settlements occur when the displacement is unequal in the foundation's base, these cause the inclination of the tank and the edge of the perimeter of the tank, generating the inclination of the liquid with the respective accumulation of tensions and deformations in an area, causing damage to

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the structure (base and bottom) and to the interconnections (pipes, nozzles). This deformation is relative, which is usually represented by the angular distortion (β) and according to [8] it is calculated by the following expression:

$$tan\beta = \frac{\Delta S_{CA}}{L_c} \quad (2)$$

where:

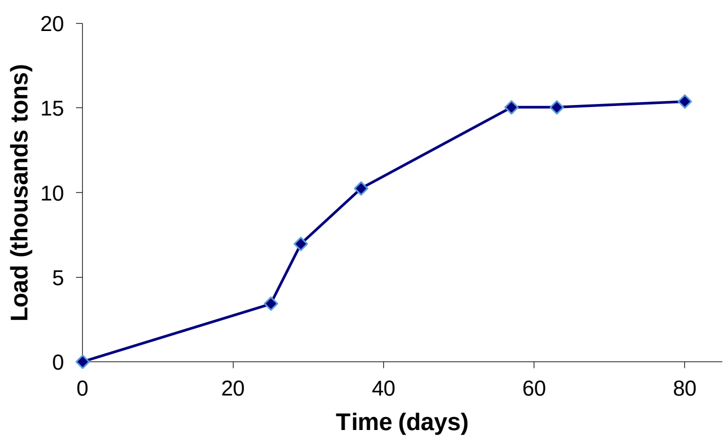
ΔS_{CA}: differential settlement between two contiguous isolated foundations or difference of vertical displacement in a section of a foundation or raft.

Lc: distance between two isolates foundations or the distance between the points where the vertical difference is measured in a foundation or raft.

Variables for water load test

Both the geodetic method to numerical modeling to define the periodicity of measurements and calculation of settlements during load testing water, was established as a fundamental criterion load growth on the basis of the foundation (0, 25, 50, 75 and 100%). Fig 2.

Figure 2: Water load test.



Different variables were considered, for each period and cycle, in order to obtain the settlement's measurements and numerical models [7]. Table 1.

Table 1: Variables for each period or cycles.

Variables / Cycle	1	2	3	4	5	6	7
Time (days)	0	25	29	37	57	63	80
Load (t)	0	3	7,0	10,3	15,0	15,0	15,4
Height (m)	0	5	10.2	15	22	22	22.5
% fill	0	26	46	68	100	100	102
Tension (kN/m^2)	38	88	140	188	258	258	264

In order to determine the heights of the reference and control points a second level high precision geometric leveling was used, since its foundation is mainly based on clay soils of low compressibility [16] , with a mean square error in the determination of the heights of ± 2.0 mm and the closure error of the leveling (fh) was calculated by the formula:

$$f_h = \pm 0.5mm\sqrt{n} \qquad (3)$$

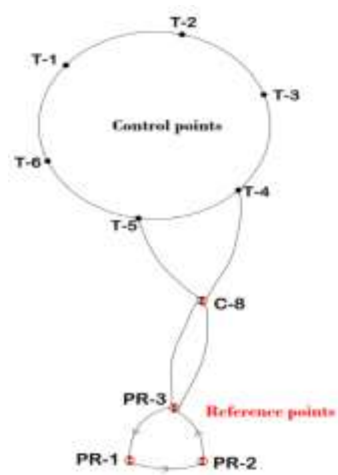
where:

n: number of instrument stations.

The analysis of the stability of the points of reference of the objects studied was carried out in correspondence with [16]. The results obtained are reliable and satisfy the requirements for the integrated study of the deformations, assuming that the values of the determined displacements are not influenced by the initial data.

The object is controlled from three main references (PR-1, PR-2, PR-3) and auxiliary point C8, located outside the area of influence of the bulb of pressures exerted by the foundation. For the monitoring of the settlements at the base of the tank, six control points (T1 to T6) were placed around its perimeter. Fig. 3.

Figure 3: Outline of the reference base and control points.

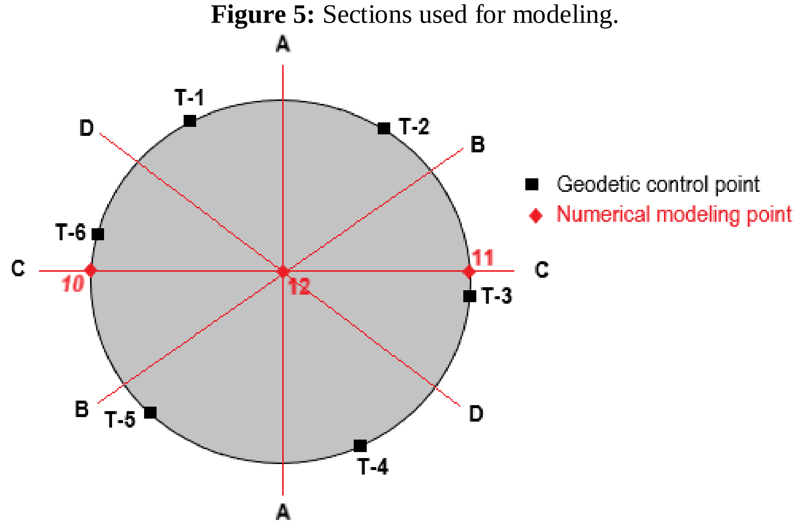


The measurements were made with a high precision level, WILD N3 optical micrometer and invar sights from 1m to 3m. According to [16-18], in each cycle that was carried out the measurements for the method of the geometric leveling of high precision was continued, maintaining the same technical requirements and the adjustment of the observations for the principle of the least squares.

Numerical modeling by FEM

For the construction and configuration of the model for the SIGMA/W module of the Geostudio 2012 software according to [19], it was necessary to define a typical section, as part of the simplification of the numerical analysis by the finite element method (FEM), these was possible due to the homogeneity existing in the soil layers that support the foundation and also to the hypothesis of establishing the areas where the greatest deformation is expected, defining four sections (A, B, C and D), which include the points located at the ends (10 and 11) of the perimeter and point 12 at the center of the base. The section C-C will be used for the comparative analysis keeping in mind its vicinity with the geodesic control points that experienced the biggest deformation. Fig. 5.

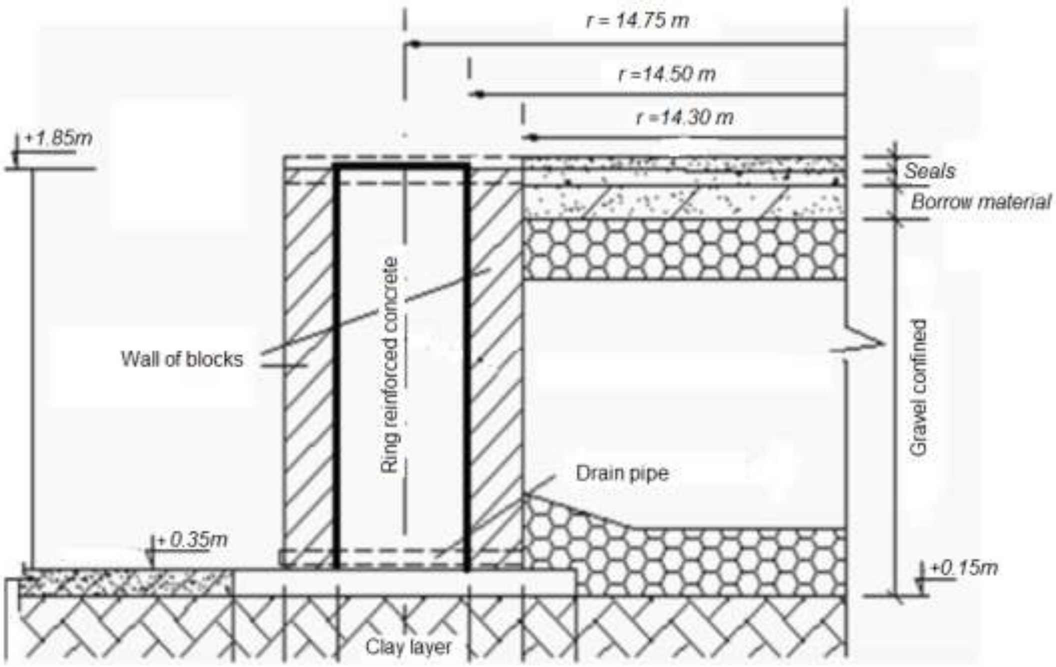
Figure 5: Sections used for modeling.



Structural and geotechnical characteristics

The superstructure was cemented on a circular reinforced concrete ring 0.9 m thick, 1.40 m above the ground surface. The dead weight of the structure is approximately 3,000 t. Fig. 6 shows the characteristics of the foundation [20].

Figure 6: Detail of the tank foundation.



The foundation rests on a homogeneous clay layer with an average value of 6.10 m. Table 2 shows the properties of the different soil layers, taken from the geological engineer report of the work [20].

Table 2: Soil characteristics.

Soil	Material properties				
	E (kN/m^2)	***v***	**ɣ** (kN/m^3)	**C** (kN/m^2)	**φ^0**
White calcareous clay	13300	0.49	19.6	20	11
Gray fine sand	33000	0.49	20.5	-	30
Sandy clay of brown color Clay	10000	0.49	19.3	30	20

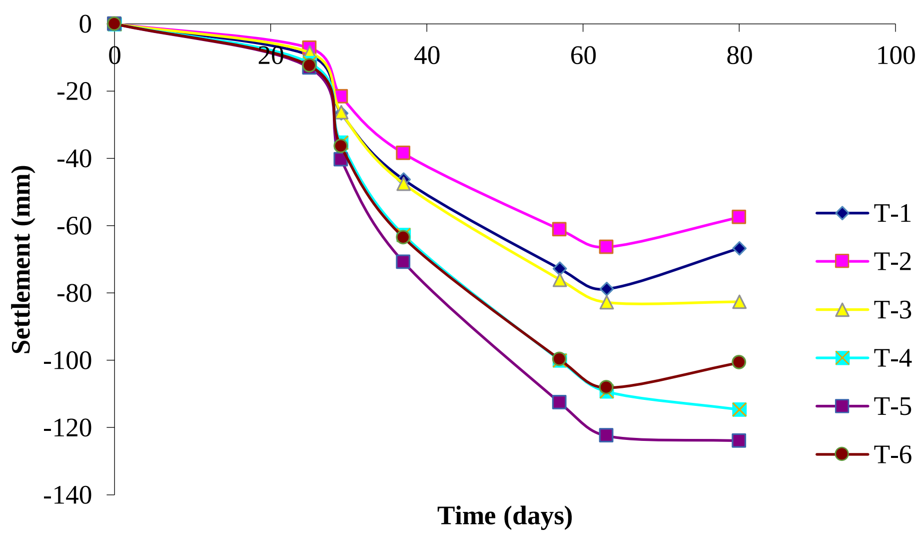
Results and discussion

Determination of settlements for the geodetic method

The observations started during the water load test, from which the tank was gradually filled to 15,000 t in about 88 days. The water was maintained for a week with 100% filling, then an overload (102%)

was applied, which was maintained for 17 days and finally was slowly emptied (unloading) in a period of eight days. The behavior of the settlements of the control points is shown in Fig. 7.

Figure 7: Settlement of control points.



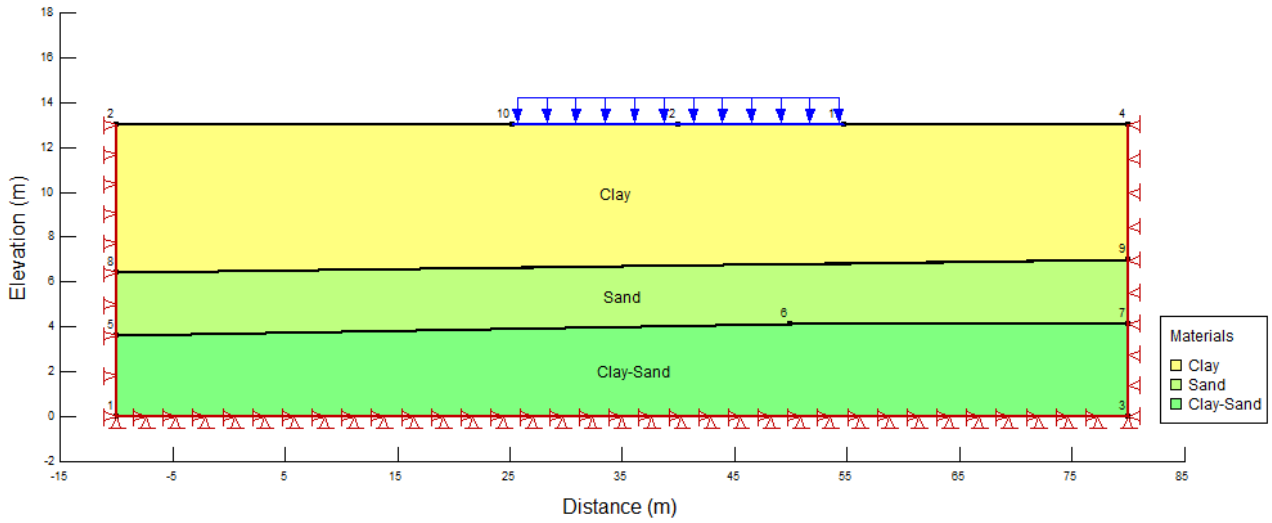
In the previous figure, it can be seen that the vertical displacements of the control points, generally follow the tank loading and unloading process, aspect that suggests two processes in the curve of the settlements of the structure [4], the first a linear behavior and the second non-linear. Starting from the cycle 3 of observations a differential character is appreciated in the behavior of the settlements, with the most representative values in the T4, T5 and T6 control points that have reached the mean values absolute maxima of 94.6 mm and 91.0 mm respectively in the cycles 6 and 7.

From cycle five (100% of the load) there is a tendency to attenuate the settlements, independently that this load is maintained for a period of six days, in addition to constantly applying an overload (102%) for 17 days and the unloading process that can be seen in the last section of the curve. This tendency to attenuate the deformations corresponds to the rearrangement of the soil particles as part of the soil consolidation process.

Settlements calculation by FEM

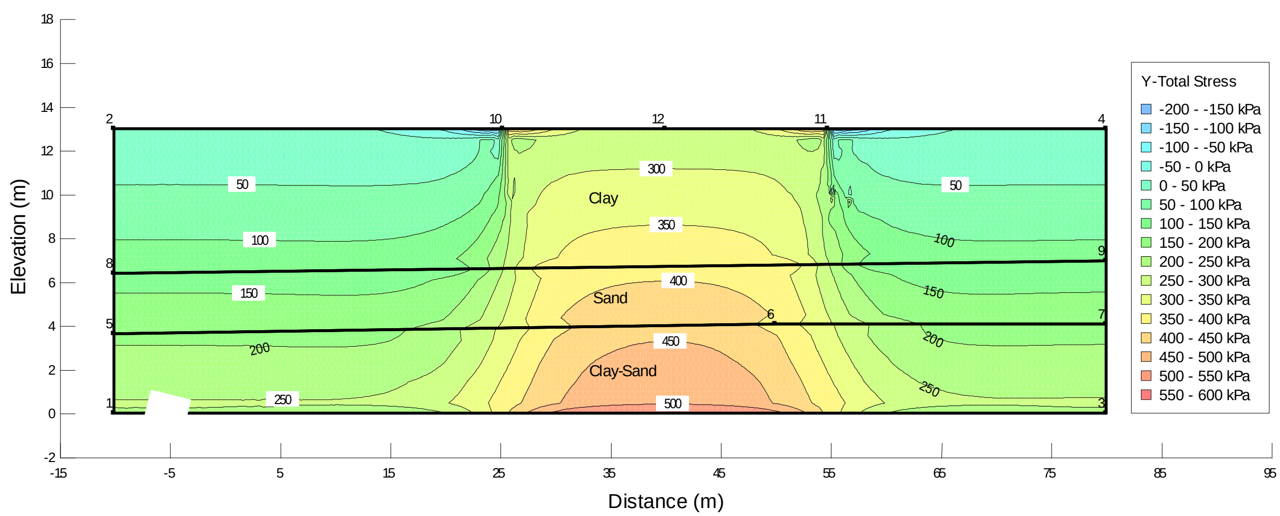
The use of the tools of the SIGMA/W module of the Geostudio 2012 software allowed to draw the C-C section (illustrated in Fig. 5) and afterwards assign the materials and the loads. Fig. 8.

Figure 8: Drawing of section C-C and assignment of materials.



As part of the results the diagrams of stresses can portray the different load steps during the test of the load of water, from the cycle 1 up to the 7. Fig. 9 shows the values of the total stresses for the last cycle, in order to be more representative for this type of analysis.

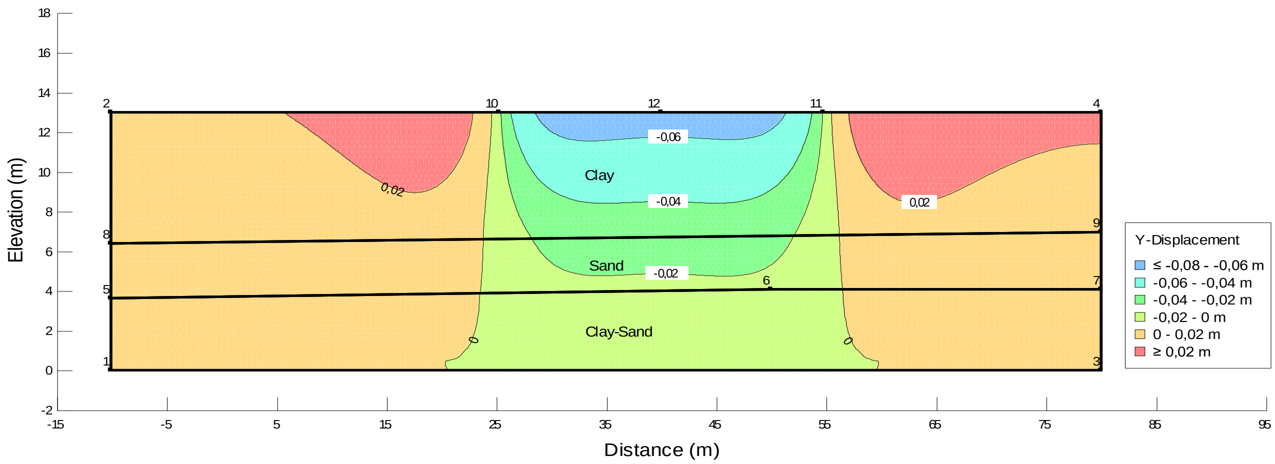
Figure 9: Total stresses model during the water load test.



The calculations of settlements were perform with the modulate Sigma/W of the software Geostudio 8 [19], for different loading steps in correspondence with the measurement periods that were kept in mind for the geodetic method, achieving continuity in the monitoring and being able to correlate and visualize the results of the displacements for each cycle.

Fig. 10 shows the results of the calculation of the settlements, taking as the most representative case the last cycle, where there are expected the highest values of settlements, due to the 100% of the load that has been reached on the base of the foundation.

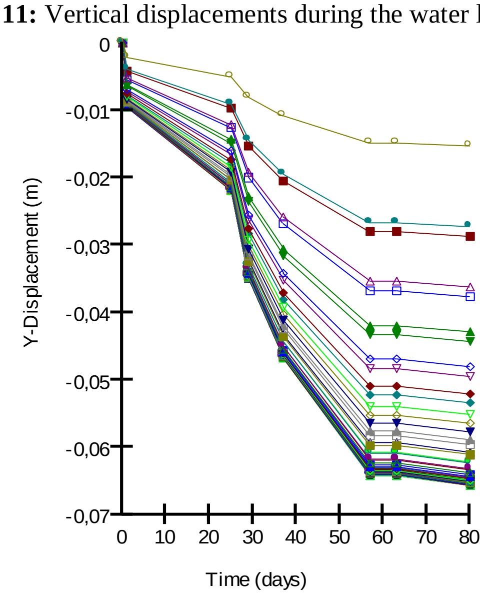
Figure 10: Absolute maximum settlements for the last cycle.



The absolute maximum displacements are observed in the upper stratum (clay), with a value of 80 mm, once it advances towards the lower strata at the border of the active power these values decrease significantly, becoming negligible for this type of analysis.

The software Geostudio 8 provides different reports on the modeling results, within which we can visualize the summary of the values of the vertical displacements for all the cycles. Fig. 11.

Figure 11: Vertical displacements during the water load test.



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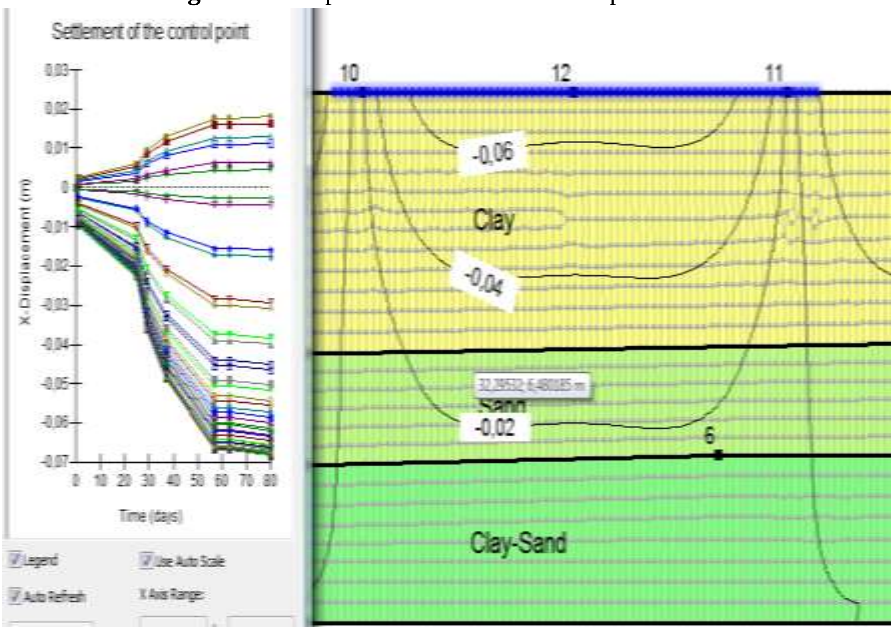
In Fig. 12 the displacements of the points can be observed in the section C-C, characterized by a marked rising (rise) of the points located near the perimeter of the foundation. However the points located in the base of the foundation tend to settle.

Figure 12: Displacement behavior of the points in section C-C.



Comparative analysis

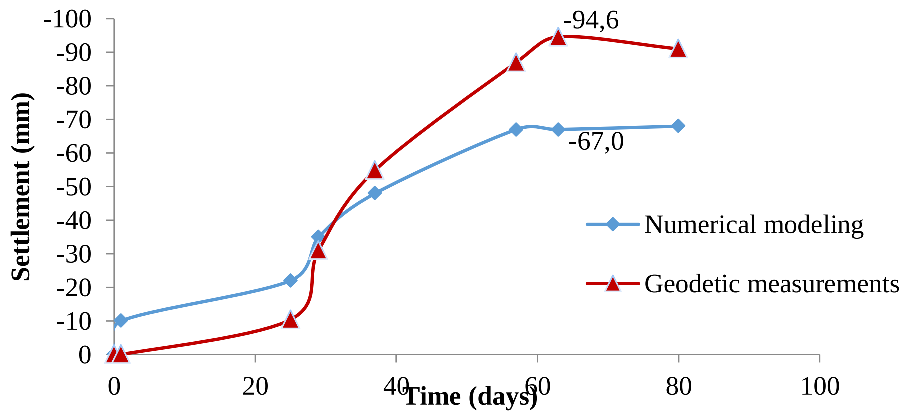
The comparative analysis was carried out taking as a standard the values of the average settlements determined by the geodetic method, with the displacements calculated by the numerical modeling by the SIGMA/W module. The results are shown in Table 3.

Table 3: Comparative analysis.

Method/ Cycle	Absolute maximum settlement (mm)							$\Delta_{máx}$ (mm)
	1	2	3	4	5	6	7	
Geodetic	0	10.4	31.1	54.9	87.0	94.6	91.0	0
FEM	10.0	22.0	35.0	48.0	67.0	67.0	68.0	27.6

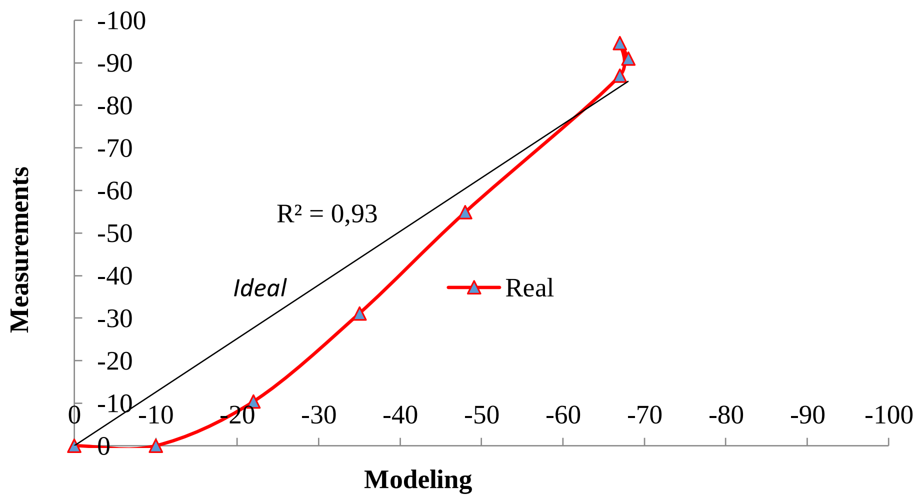
The differences (Δ) between the settlements determined by the geodetic method and those obtained by the deterministic modeling remain constant in most cycles, with the highest value of -27.6 mm in cycle 6, matching with the moment when the greatest load is applied. For the last three periods, the differences of the settlements (measured and calculated) do not exceed the maximum error of their determination [15], which indicates that they show a tendency to attenuation, product of the rearrangement of the particles during the soil consolidation process. Fig. 13.

Figura 13: Time series of settlements observed by geodetic method and computed by FEM.



In general, it can be observed that there is a good correlation between the pattern of the curves, the average settlement measured (geodetic method) and the one calculated by FEM, during the water load test. This correlation can be improved considering that for the first cycle an initial settlement value of 10 mm is calculated by the numerical method, which is produced by the own weight of the soil, which cannot be determined by the geodetic method and is assumed a value equal to zero, which demonstrates the feasibility of the SIGMA/W module for the calculation and forecast of settlements in the bases of the foundations of the fuel depots.   Fig. 14.

Figure 14: Analysis of the correlation between the measured and calculated values.



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Conclusions

This study presents an analysis of the deformation for the monitoring during a water load test in a fuel storage tan from the integration of the geodesic and numerical method. The measured settlements have been compared using the high-precision leveling with the calculated for the numerical modeling by FEM. This comparison reveals that a good correlation exists between the values of the settlements obtained by the geodetic method and those calculated by the numerical method, the greatest difference being -27.6 mm, which is considered admissible for this type of structure, demonstrating the feasibility of the use of the GeoStudio 8 Software for the modeling and prediction of the vertical displacements from the use of its SIGMA/W module. The results show the suitability of using the geodetic method as a standard for the verification and improvement of the methods of numerical modeling.

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References

1. Guler G et al. Evaluation of the Movements of the Dam Embankments by Means of Geo-detic and Geotechnical Methods, J. Surv. Eng, pp. 132: 31–39, USA, 2006.
2. Szostak-Chrzanowski, A. Interdisciplinary Approach to Deformation Analysis in Engineer-ing, Mining, and Geosciences Projects by Combining Monitoring Surveys with Deterministic Modeling—Part I; Technical Science, Paper and Report, No. 9; University of Warmia and Mazury: Olsztyn, Poland, 2006; pp. 147–172.13.
3. Vassilis, G.; Sakellariou, M. Settlement analysis of the Mornos earth dam (Greece): Evi-dence from numerical modeling and geodetic monitoring. Eng. Struct. 2008, 30, 3074–3081.
4. Recarey, C.A. Modeling of the land and structures in the domain of time, Doctoral thesis, Central University ¨Marta Abreu¨, Villa Clara, 1999.

5. Acosta, L.E; De Lacy, M.C.; Ricardo,S.E; García, J.; Hernández, O. Analysis of the ge-otechnical vulnerability in the works of engineering of the nickeled region of Holguin starting from the employment of geodesic methods. RBCT 2018, 45, pp. 5-13.
6. Gonzalez, M. The land, Ed. UPC, Spain, 2001.
7. Acosta, L. E. Geodesic monitoring of settling in vertical fuel tanks", Mining y Geology Vol. 33, No.3, pp. 266-278, Moa, 2017.
8. NC 1321. Norm for geotechnical design of shallow foundations. La Havana, Cuba, 2019.
9. Application of the States Limits and Theory of Security in the Geotechnical Design in Cuba , Doctoral Thesis in Sciences, Central University ¨Marta Abreu¨, Villa Clara, 2002.
10. Pytharouli, S.I.; Stiros, S.C. Investigation of the parameters controlling the crest settle-ment of a major earthfill dam based on the threshold correlation analysis. J. Appl. Geod. 2009, 3, 55–62.
11. Yigit, C.E.; Alcay, S.; Ceylan, A. Displacement response of a concrete arch dam to sea-sonal temperature fluctuations and reservoir level rise during the first filling period: Evidence from geodetic data. Geomatics. Nat. Hazards Risk 2016, 7, 1489–1505.
12. Acosta, L.E; De Lacy, M.C.; Ramos, M.I.; Cano, J.P.; Franco, O.D.; Herrera, A.M.; Avilés, M.; Gil, A.J. Displacements Study of an Earth Fill Dam Based on High Precision Geodetic Monitoring and Numerical Modeling . Sensors 2018, 18, 1369.
13. API 653. Tank Inspection, Repair, Alteration, and Reconstruction, American Petroleum Institute, Fourth edition, Washington, D.C, USA, 2009.
14. Mayorga, M.O. Physical inspection and structural analysis to determine the operative-ness of a vertical cylindrical tank for storage of Fuel Oil according to API 653 standard after an accident, Diploma Work, Polytechnic School of the Litoral, Guayaquil, Ecuador, 2013.
15. USACE.EM.1110-2-1009: Structural deformation Surveying, Washington, DC 20314-1000, USA, 2002.

16. MET 30-27. Methodology for the control of deformations of works starting from geodetic methods, Geocuba, La Havana, Cuba, 2004.
17. Savvaidis, P. Long term geodetic monitoring of the deformation of a liquid storage tank founded on piles, Proceedings, 11th FIG Symposium on Deformation Measurements, Santo-rini, Greece, 2003.
18. De Lacy, M.C.; Ramos, M.I.; Gil, A.J.; Franco, O.D.; Herrera, A.M.; Avilés, M.; Domínguez, A.; Chica, J.C. Monitoring of vertical deformations by means high-precision geodetic level-ing. Test case: The Arenoso dam (South of Spain). J. Appl. Geod. 2017, 11, 31–41.
19. User Manual "Stress-Deformation Modeling with SIGMA/W", An Engineering Methodol-ogy; GEO-SLOPE International Ltd.: Calgary, AB, Canada, 2013.
20. ENIA. Report on the engineer-geological investigations for the construction of the CTE of Felton, Holguín, Cuba, 1998.