Evaluation of the Performance of Waterproof Perimeter Barriers

Numerical and Physical Models

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Abstract

Collapsible soils cover a great part of Córdoba city in Argentina. Loessian soil is formed by silt and sand particles with clay bridges, generating macropores susceptible to collapse upon wetting under load. Those structures that are superficially supported on this type of soils are susceptible of suffering damage because of soil wetting. Some actions can be taken to prevent the effect of this phenomenon, such as trays for pipes, storm drains, deeper foundations and perimetral sidewalks. At present, there is no literature about the design or hydraulic behavior of perimetral sidewalks.

In this paper different types of barriers are going to be implemented in numerical and physical models. The purpose is to analyze and evaluate the barriers performance to avoid supporting soil wetting and settlement of foundations due to soil collapse. In this sense, a shallow foundation prototype was constructed and different perimetral barriers were materialized. A design rainfall was applied over the model. Simultaneously, this prototype was implemented in a finite element software to validate numerical results with physical ones. The characterization of the materials that constitute the proposed barriers and foundation soil are carried out to the numerical models.

Obtained results allow making the evaluation of performance of the different implemented barriers validating the numerical model results and making some recommendations for the proper design of waterproof perimeter barriers.

Keywords

Perimetral Barriers; Collapsible Soils; Construction Pathology

Introduction

All buildings usually show some degree of cracking. In some cases fissures are notorious and produce concern but in other cases they are not visible by the naked eyes. Fractures in general (whether fissures or cracks) show different configurations: vertical, inclined or horizontal. The cracks could be classified as static (if they do not change over time) or dynamic (if they constantly change) according to their level of activity (Bernal, 2008).

In general, but particularly in low-rise buildings, 90% of fissures and cracks are caused by the movement of foundation soil, and produce pathological injuries. The injury is *direct* if damage begins in foundation elements (underground), and *indirect* when cracks are lagging damage in walls or structural elements caused by soil-foundation movement.

Direct injuries are improbable because foundation structures, generally, are well designed. Instead, ground movements or other processes involving instability in microstructure provoque indirect injuries in the soil-foundation-structure system and failures in some elements of the building (Bernal, 2008).

Soils of Córdoba City

Loessian soils cover a great part of Córdoba city. The main characteristic of primary loess is its high unstable structure and its susceptibility to suffer large volumen changes in presence of water. This collapse process does not need complete soil saturation to occur. Processes involved in soil collapse have been extensively studied in the literature for Argentine loess (Reginatto y Ferrero, 1973; Redolfi, 1982; Roca et al., 1992; Rinaldi et al., 2007) and for other deposits in the world (Dudley, 1970; Barden et al., 1973). Wetting effect causes a decrease in the capillary attraction forces (matric suction) between particles of clay and leads to a weakening of the structure and closing the pores of the soil.

Wetting effect causes variations in the microstructural behavior of loess, generating injuries to the structures supported on it. Soil-water interaction weakens the original structure solving soluble bonds and inducing important settlements and surface erosion.

Some authors make recommendations that could be taken into account when building on soils prone to suffer wetting collapse processes under a determined load. These contributions should be validated by numerical and physical modeling (Aitchinson, 1973; Evstatiev, 1988; Redolfi, 2007). In Córdoba this phenomenon causes serious indirect injuries and economic losses due to damage in buildings, especially in the most vulnerable social groups. In this sense, it is relevant to study different alternative solutions to prevent damage in constructions.

In this work, the most relevant parameters to describe loessian soil behavior were determined from a large number of laboratory and in situ tests (TABLE 1). Loess shows a weak cementation level, induced by soluble salts, amorphous silica, calcium carbonate, gypsum and iron oxide (Capdevila, 2008). This set of parameters will be considered in the numerical modeling of the proposed situation.

TABLE 1 PARAMETERS OF LOESSIAN SUPPORT SOIL

Material	Depth [m]	Dry unit weight [kN/m³]	Hydraulic conductivity [m/sec]
Loess	1	12.50	10^{-7}

Waterproof Perimetral Barriers

One of the main preventive actions to avoid soil collapse because of the entry of rain water into soil foundations is the "perimeter sidewalk". In this paper the term "sidewalk" will be replaced by the name of impermeable perimeter barrier because these barriers could not necessarily be located on ground surface, but at depth to hide them, to improve the aesthetics of the buildings.

This article proposes to model numerically a series of impermeable perimeter barriers attached to a wall in order to evaluate its efficiency and provide design conditions, to be later implemented in a physical scale model. A brief description of each of the proposed alternatives is presented along with a soil foundation characterization.

Concrete Perimetral Sidewalk

Most commonly impermeable perimetral barriers used in order to keep away rainwater from shallow foundations are perimetral sidewalks. These elements are performed by a concrete subflooring 10cm thickness and 50cm width, leaving it visually incorporated into the building. Hydraulic conductivity is the most relevant parameter in the design of a perimetral sidewalk as opposed to compressive strength, as in most concrete structures.

The concrete hydraulic conductivity is between 10^{-8} and 10^{-12} m/sec. These values consider permeability to pressure water (according to UNE -EN 12390-8), so it results conservative with respect to the proposed situation.

Soil-bentonite Compacted Barrier

This is a compacted soil barrier obtained from a mixture of loess soil from the center of Argentina and bentonite. The incorporation of this type of clay reduce the hydraulic conductivity due to its property of expansiveness and low permeability (Evangelista and Clariá, 2008; Francisca and Glatstein, 2010).

Compacted loessian soils reach values of hydraulic conductivity in the order of 10^{-8} m/sec which result insufficient for the use in impermeable barriers, being necessary to decrease these values. The addition of bentonite or other clay mineral reduces the value of permeability to improve its performance (Malusis et al., 2009; Francisca and Glatstein, 2010).

The parameters necessary to numerical modelling were taken from samples compacted by Standard Proctor compaction test. Adopted bentonite content was 3% by weight, with good results obtained (Evangelista and Clariá, 2008).

High Density Polyethylene Barrier

This proposed barrier consists of a high density polyethylene geomembrane (HDPE). Regarding to the execution of barriers used in a solid waste landfill, international normative regulates minimum thickness to be adopted in this membrane (Rowe et al., 2010). In this paper HDPE is implemented as a layer to prevent the entry of rainwater from generating a draining surface disposed slightly buried.

The main problems in membranes of polymeric materials are aging or degradation over time, being the most common ultraviolet radiation (UV) and thermal degradation. In order to determine the hydraulic conductivity of this geomembrane, manufacturers comply with E-96 ASTM normative (Maxwell et al., 2005).

Polyvinyl Chloride Barrier

This barrier includes a PVC geomembrane of 1mm thickness. These membranes are mainly characterized by their high biaxial flexibility to an easy surface accommodation, even with important differential settlements, and to maintain its properties with a constant value over a wide temperature range. They also have a low permeability, relevant for use in this work. TABLE 2 shows a summary of the hydraulic conductivity of the proposed barrier.

TABLE 2 PARAMETERS OF IMPERMEABLE PERIMETER BARRIERS

Material	Dry unit weight [kN/m³]	Hydraulic conductivity [m/sec]
Concrete	22.00	10^{-12}
Soil-bentonite	15.40	$4x10^{-10}$
HDPE	9.40	10^{-15}
PVC	9.50	10^{-11}

Numerical Modelling

Numerical modelling of the proposed perimeter barriers was carried out in the finite element software SEEP/W. The software allows modelling just a half of the shallow foundations, including the support soil. FIG. 1 shows the model implemented in SEEP/W. It could be noted the designation of different elements and the dimensions adopted by each.

The proposed model in this work mainly includes the hydraulic behavior of different elements. In this regard an unsaturated model was adopted for loessian soil, being necessary to adopt the soil-water characteristic curves and the variation of hydraulic conductivity with variation of suction. The same model was used to implement the proposed perimeter barriers, except for the geomembrane ones (HDPE and PVC) included in the software as elements of interface. FIG. 2 shows the proposed schemes for modeling various proposals perimeter barriers.

FIG. 2 also shows that concrete sidewalk (a) was placed on the surface, while in the other three alternatives (b, c and d) the barrier was placed 20 cm depth so as to hide it not to affect the aesthetics of the building. The concrete sidewalk was modeled 10cm thickness, the same as compacted soil-bentonite, whereas HDPE and PVC geomembrane barriers were modelled as interface elements. All the barriers were modeled with 0.50m width. After completion of the model, boundary conditions were incorporated, as shown in FIG. 3. Lower boundary presents 80 kPa of initial suction of 80kPa according to natural moisture content of loessian soil (w = 10%) at 2m depth. Over the upper boundary, adjacent to shallow foundation, rainfall was applied for one hour of $2.2x10^{-8}$ m/s, equivalent to 700 mm/year, corresponding to average annual rainfall record for Córdoba

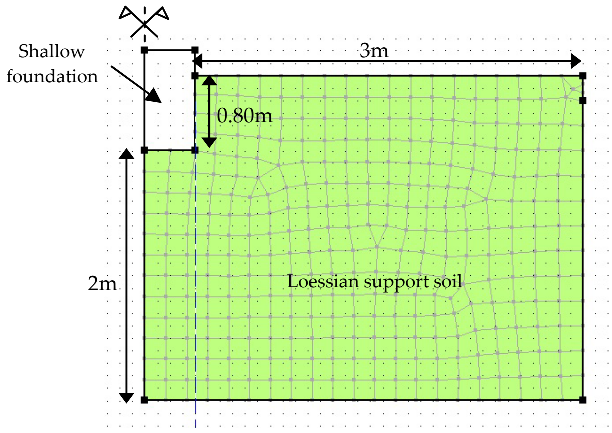

FIG. 1 SCHEME OF THE MODEL IMPLEMENTED IN SOFTWARE SEEP/W, WITH FINITE ELEMENT MESH.

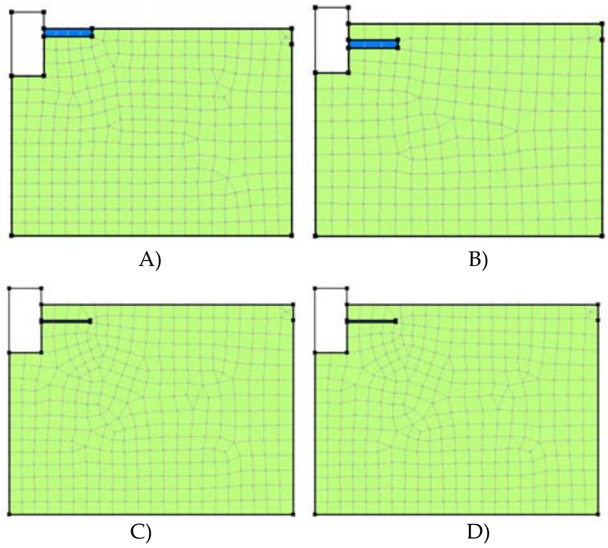

FIG. 2 SCHEME OF THE MODEL IMPLEMENTED IN SOFTWARE SEEP/W WITH THE DIFFERENT BARRIERS. A) MODEL WITH DE CONCRETE SIDEWALK. B) SOIL-BENTONITE COMPACTED BARRIER. C) HDPE GEOMEMBRANE. D) PVC GEOMEMBRANE

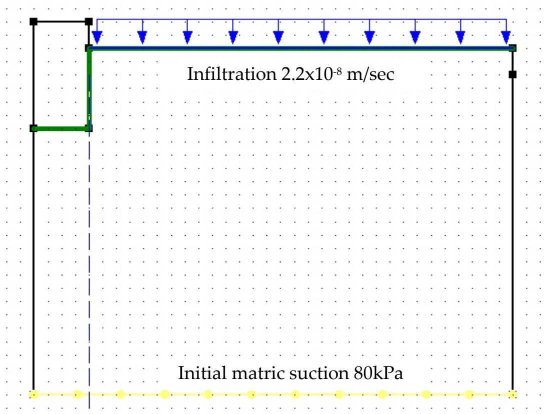

FIG. 3 SCHEME OF THE MODEL IMPLEMENTED IN SOFTWARE SEEP/W WITH BOUNDARY CONDITIONS.

Physical Model

The materialization of impermeable perimeter barriers was performed from insertion into a scale model of a concrete shallow foundation. This foundation system is generally used in affordable housing. The foundation was made with low-strength concrete, with a volume dosage of 1:3:3 (Portland cement:coarse sand:pellets up to 50mm) and with dimensions of 0.40m width, 0.40m height, 5m length and disposed at 0.80m depth. Then, three rows of ceramic blocks were arranged and settled with lime mortar, as indicated in the scheme of FIG. 4a, and can be observed in the photographs of FIG. 5.

The wall-foundation system was divided into five sections of 1m length, with one type of perimeter barrier disposed on each section. The first section remains uncovered (see FIG. 4b).

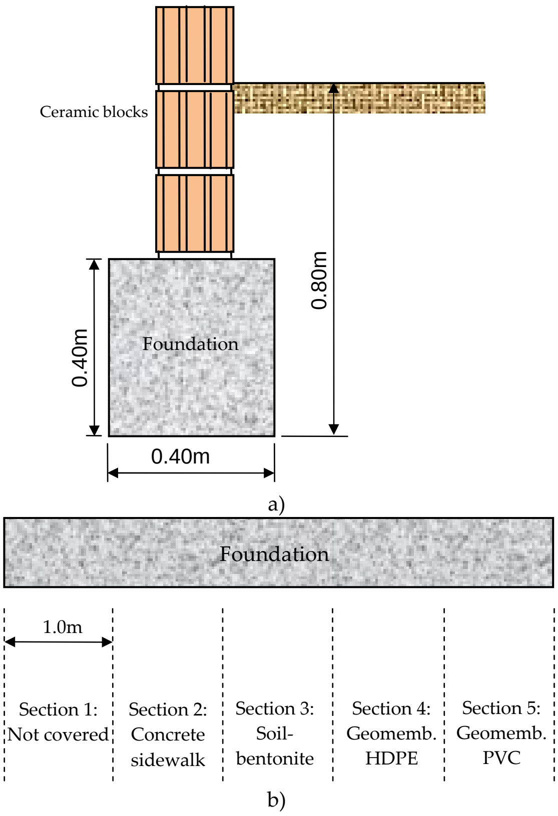

FIG. 4 SCHEME OF THE PHYSICAL MODEL IMPLEMENTED. a) CROSS-SECTION. b) PLANT.

FIG. 5 IMAGES OF THE CONSTRUCTION OF THE PHYSICAL MODEL. A) FOUNDATION CONSTRUCTION. B) LAYING CERAMIC BLOCKS.

As the ceramic block wall raises, different perimeter barriers were implemented in the proposed sections of 1m length (see Figure 4b). The construction procedure of each barrier is detailed below.

The implementation of the four proposed barriers involves the excavation of a 0.50m width trench adjacent to the physical model. The trench depth varies according to the type of barrier to materialize. The concrete barrier was placed superficially; therefore, in this section, the trench was excavated 0.10m depth, corresponding to the thickness of the perimeter sidewalk. This sidewalk was made with a dosage 1:3:3 (Portland cement: coarse sand: 50mm pellet) in volume. The soil-bentonite barrier was manually compacted by a rammer to a depth of 0.20m, 0.10m thickness and a content of bentonite of 3% by weight. In order to ensure the sealing of the joint, a polyethylene film of 200 μm thickness was placed in the middle of the thickness of these two barriers and inserted between two rows of ceramic blocks.

The other two barriers were executed at 0.20m depth, where the geomembrane was placed over natural soil previously compacted. The excessive membrane was inserted into blocks joint to ensure the wall-barrier junction.

Natural soil was disposed over the three buried barriers in order to hide them, not to affect the building aesthectics. Figures 6, 7 and 8 show construction sequence.

In order to avoid the rainfall water entry, a polyethylene film of 5m length and 3m width was disposed adjacent to the foundation/wall system in the opposite side to the barriers.

FIG. 6 POLYETHILENE FILM TO ENSURE THE WALL-BARRIER JUNCTION

FIG. 7 CONSTRUCTION OF SOIL-BENTONITE BARRIER. PLACEMENT OF POLYETHYLENE FILM TO SEAL JOINT BETWEEN WALL AND BARRIER

FIG. 8 GEOMEMBRANE BARRIER EXECUTED WITH POLYVINYL CHLORIDE (PVC) INSERTED INTO THE WALL AND AT 0.20M DEEP

Test Procedure

The test performed on the scale model consisted of moistening the adjacent area to the model, from the wall face to a distance of 2m, in accordance with the proposed numerical model, and 5m length. First, it was necessary to define the design rainfall, determining the volume of water to be incorporated to the model under similar conditions this type of foundation presents in Córdoba city.

According to the rainfall record in Córdoba from 1981 to 1990, the wettest month was December with precipitations of 155mm (National Weather Service, 1998). In this sense, a monthly amount of rainfall of 1500 litres is expected in the surface of 10 m^2 that are going to be wetted. To perform this test, this volume of 1500 litres of water was distributed in the surface in 6 stages of 250 litres each. The distribution of water supplied in 6 watered sessions responses to the number of monthly rainfall in the period.

Water was applied by a traditional home sprinkler over a period of 30 days. Test was conducted during August, in accordance with the period of lowest rainfall of the year (if some precipitations occurred, they could be deducted from the total water volume to water).

72 hours after finishing the test, in order to allow a uniform distribution of moisture content, the impermeable barriers were removed and five trenches were digged: one in each section tested. Then, moisture content was measured using an electronic hygrometer Spectrum, model FIELDSCOUT, to depth of 0.20m, 0.40m, 0.60m and 0.80m. This procedure was carried out in the area near the foundation and also at a distance of 0.50m and 1.00m in perpendicular direction to the wall.

Results

Numerical Modelling

Results obtained after performing the modeling in the SEEP/W software are presented in this section. In all cases the figures presented show the wetting front under the foundation after modeled rainfall infiltration. FIG. 9 shows the results obtained in the model without any perimetral barrier, where the suction resulting values (in kPa) are disposed in a white box. The water content values indicated in the Figures were obtained from suction values and water-soil characteristic curve of the soil. From FIG. 9 it could be inferred that the water infiltrates unimpeded and increases markedly the moisture content up to about 0.50m deep under the shallow foundation. This situation would present major problems of settlement by wetting collapse under load.

Once the concrete sidewalk was incorporated in the model, the wetting front is modified as it can be seen in FIG. 10. Decreasing moisture content below the shallow foundation is highlighted, causing an improvement in supporting soil behavior. This effect is due to the longer path that water prosecutes in the infiltration process. However, in some areas under the foundation, some moisture content values that condition the soil behaviour were detected.

FIG. 11 presents the wetting front obtained after incorporating compacted soil-bentonite perimeter barrier, located under the ground surface. From the observation of this Figure, it could be mentioned the proper functioning of the implanted barrier. The barrier induces a significant decrease in the infiltrated water under the foundation, improving soil behavior. The subsurface location of the barrier generates an increasing in the water flow path resulting in greater loss of energy making efficient its implementation (see FIG. 12.

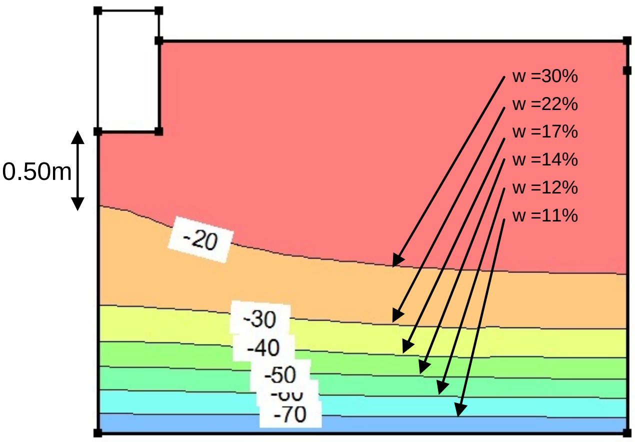

FIG. 9 WETTING FRONT ADVANCE IN THE SUPPORT SOIL EXCLUDING ANY PERIMETRAL BARRIER

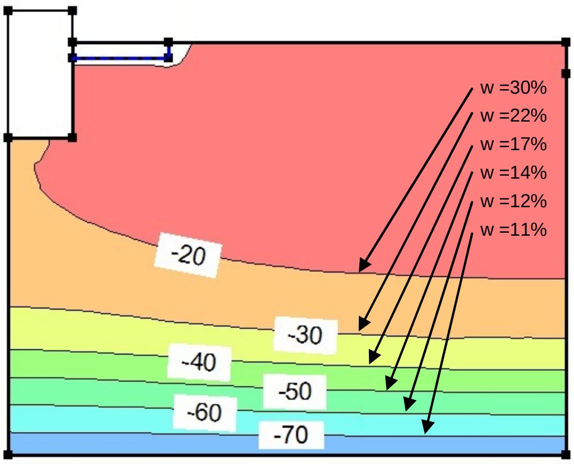

FIG. 10 WETTING FRONT ADVANCE IN THE SUPPORT SOIL WITH CONCRETE SIDEWALK PERIMETRAL BARRIER

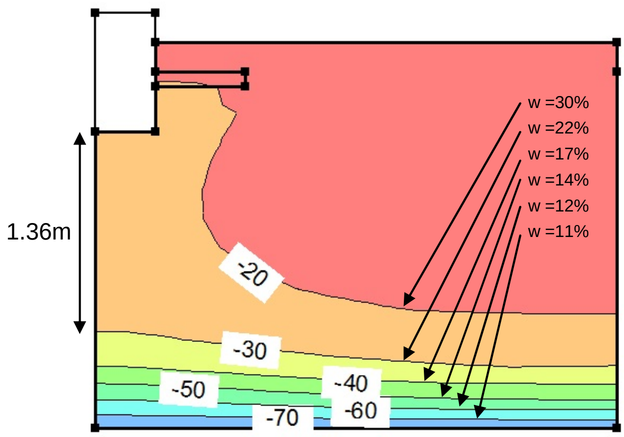

FIG. 11 WETTING FRONT ADVANCE IN THE SUPPORT SOIL WITH COMPACTED SOIL-BENTONITE PERIMETRAL BARRIER

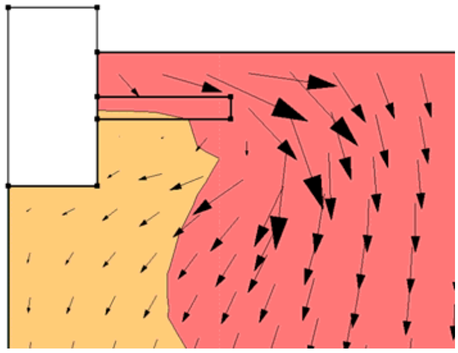

FIG. 12 FLOW VECTORS INDICATING THE PATH OF INFILTRATED WATER WHEN THE BARRIERS ARE BURIED

The resulting wetting front with the inclusion of the third alternative of perimeter barrier on the numerical model is shown in FIG. 13. The PVC geomembranes is also subsurface disposed, presenting a similar hydraulic behavior with respect to the soil-bentonite compacted barrier, in relation to its effectiveness.

The last of the proposed barriers is the HDPE geomembrane. FIG. 14 presents the variation of the degree of saturation of the support soil, highlighting a similar behavior to the previous two barriers.

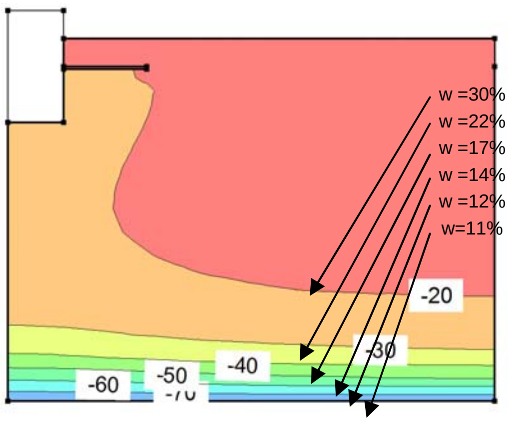

FIG. 13 WETTING FRONT ADVANCE IN THE SUPPORT SOIL WITH PVC PERIMETRAL BARRIER

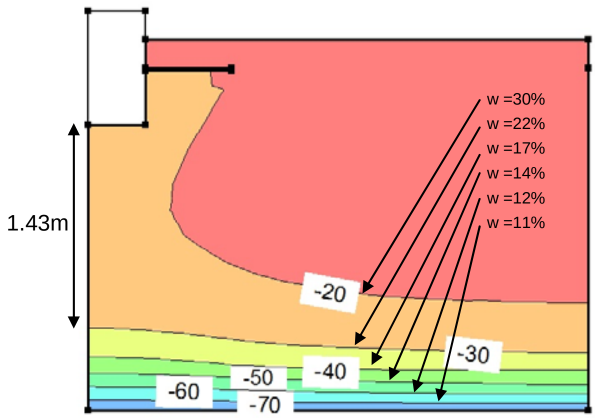

FIG. 14 WETTING FRONT ADVANCE IN THE SUPPORT SOIL WITH HDPE PERIMETRAL BARRIER

From the results observed in Figures 11, 13 and 14, it can be discussed that the thickness of the perimeter barrier is not a relevant parameter to analyze the barrier efficiency because the last three ones exhibit similar behavior. Thus, the hydraulic conductivity is the parameter that governs the system behavior.

Physical Model

The moisture content measurements made by the soil moisture sensor allowed determining a curve of the wetting front as a function of depth, next to the wall and foundation and in nearby areas. FIG. 15 plots the moisture content profile adjacent to the wall/foundation for depths of 0.20m, 0.40m, 0.60m and 0.80m, and depending on the type of applied impermeable barrier. It is also included the moisture variation in the section without barriers.

FIG. 15 stands out the efficiency of the different barriers preventing the entry of water flow in areas near the foundation. A similar effect occurs between soil-bentonite compacted barriers, HDPE and PVC geomembranes, while the concrete sidewalk slightly facilitates the entry of water, which checks the results of numerical modelling shown in Figures 11, 13 and 14. This behavior could be based on the relative location of the impermeable barriers, considering that the concrete sidewalk was disposed on the surface and the other ones were located at 0.20m depth. In this sense the infiltration water on buried barriers has longer and slower path than the one in the concrete sidewalk to reach the soil under the foundation, assuming a correct joint sealing between the barriers and the wall. Besides, the subsurface arrangement of the barriers allows to hide its existence not to affect the aesthetics of the building

Obtained results show that the hydraulic conductivity of the material used in impermeable perimeter barrier results irrelevant for values less than 10^{-10} m/sec. In this sense, it could be used the cheapest material, considering both, acquisition and implementation costs, but highlighting the relevance of the appropriate execution of the joint between the wall and the barrier. In the case of soil-bentonite compacted barrier, it is necessary to include a polyethylene film within the barrier and linked to the wall through the joints between ceramic blocks. In geomembrane barriers, the end of the membrane is folded and inserted on the ceramic blocks joint.

FIG. 15 also shows that the moisture values of the supporting soil, under barriers and at the foundation depth are slightly higher than the typical natural moisture content in loessian argentinian soils (less than 12%). This moisture content after wetting does not modify soil structure, guaranteeing its stability.

In FIG. 16 it is shown the variation of moisture content in accordance with the depth for the soil-bentonite compacted barrier for measurements performed in the area of the physical scale model, at 0.00m, 0.50m and 1.00m away from the wall face. The tendency is the same than in the other barriers. The observed behavior is within what it is expected for this type of testing.

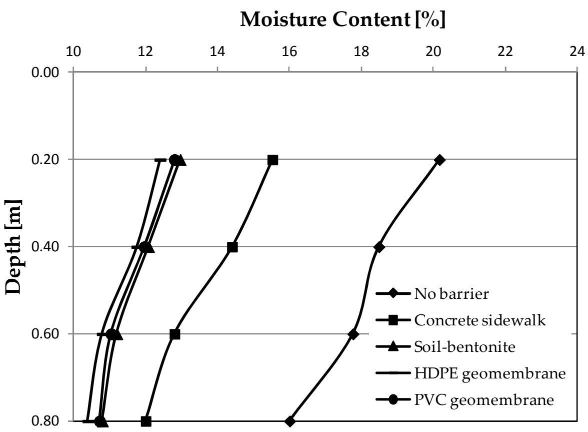

FIG. 15 MOISTURE PROFILES OBTAINED UNDER THE PROPOSED BARRIERS NEXT TO FOUNDATION AND WALL

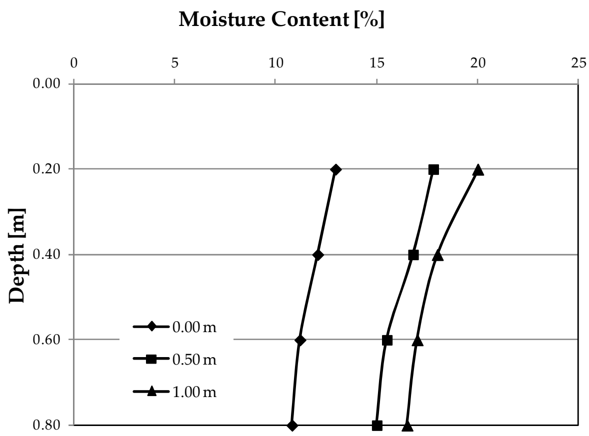

FIG. 16 MOISTURE PROFILES OBTAINED UNDER THE SOIL-BENTONITE COMPACTED BARRIER AT 0.00M, 1.00M 0.50M AWAY FROM THE WALL FACE

Conclusions

From the results presented in this paper, the following conclusions could be made:

1. In the presence of a shallow foundation and loessian silty supporting soils potentially collapsible upon wetting, the inclusion of impermeable perimeter barriers is necessary in

order to decrease the presence of rainfall water under the foundation.

2. The recorded moisture contents at the foundation level in the physical model, under the implemented impermeable perimeter barriers, do not affect the stability of collapsible loessian soils, ensuring the correct operation of the foundation.
3. Results obtained from the proposed numerical model were validated with those obtained in the executed physical model. Therefore, the reliability of numerical modelling for subsequent analysis in the same research line is confirmed.
4. The buried perimeter barriers delay the water flow and increase the flow path of infiltrated rainfall water, increasing their efficiency.
5. The implementation of a polyethylene film to link the proposed barriers to the wall of the physical model was adequate to ensure the sealing of the joint.
6. Perimeter barriers materialized with soil-bentonite, HDPE and PVC geomembranes show similar and slightly higher efficiencies than concrete sidewalk.
7. The thickness of the barriers is not a relevant design parameter for improving the performance, but it is the hydraulic conductivity the parameter that governs the behavior.
8. The location of the buried perimeter barriers, besides improving the system performance, they do not affect the aesthetics of the building.

ACKNOWLEDGMENT

The authors want to acknowledge the Secretary of Science and Technology of the National University of Córdoba for their financial support support to this research.

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