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Educating Students Through Understanding the Pathology of Geotechnical Projects

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ABSTRACT

Three projects of end of studies which are related to soil mechanics pathology case histories were undertaken by students at civil engineering department of National Engineering School of Tunis. The two first projects dealt with Joumine and Sidi Saâd earth dams cases. For Joumine dam, concrete slabs of the spillway have been affected by serious disorders. The first disorder is related to the swelling nature of soil foundation of concrete slabs. The second disorder is attributed to high excess pore pressure responsible of slabs up risings. As solution the jet grouting technique was designed to eliminate high pore pressure in the soil foundation of slabs. For Sidi Saâd dam disorders were attributed to high active soil pressures exerted on retaining walls of the spillway. As solution anchored cables were adopted to improve the stability of concrete walls. The third project dealt with four engineering structures crossing Tunis La Goulette express route. All approach slabs were affected by differential settlements due to the existence of highly compressible thick soft clay layers. As solution three soil improvement techniques (rigid inclusions, stone columns prefabricated vertical drains) were compared to stop non admissible consolidation settlements. For each case history, the methodology to diagnose causes of disorders is first presented, second, the utilized approaches, especially those involving finite element codes usage, are highlighted, finally proposal of remedies to re establish suitable exploitation of projects are exposed. This paper well illustrates the great importance for under graduated students, when preparing their works of end of projects, to more understand fundamentals in soil mechanics in parallel with treating serious problems of pathology of case histories.

INTRODUCTION

Approaching broad research topics in connection with civil engineering education via practical examples became a real need for training undergraduate students. For this purpose, projects of end of studies, in engineering colleges, offer an excellent occasion. However, such an exercise is a typical wide and sophisticated subject in engineering knowledge field. To overcome difficulties related to this subject, the combination of experienced knowledge is necessary. However, engineering education can benefit from this integrative view for which knowledge model using different levels of generalization has been recently proposed (Oliveira et al., 2007). This model starts from high generality till very specific issues. The corresponding knowledge stages are the following: thematic, project, case study, problem, algorithm, operation and data.

Dealing with geotechnical engineering usually involves aspects of engineering geology, soil mechanics and applied geophysics to design a wide variety of civil and hydraulic engineering projects. As first step geotechnical campaigns are carried out to define the soil profile and geotechnical parameters of encountered layers. This will enable the design of project for which stability aspects should be handled carefully. After construction the follow up of project behaviour will show how efficient was, especially, the geotechnical investigation on which is based all the procedure of design. In case of some lack either related to insufficient soil investigation, which is the current situation, or non suitable design methods, which are less likely, then disorders will appear during the exploitation of project and its stability is again questionable.

Pathology of construction is not often taught in civil engineering education. At the same time specialists in this field are very few worldwide. But restoration of engineering structures can not be missed for several reasons. These facts imply how delicate is the treatment of affected constructions by disorders, starting by the identification of the origin of disorders, passing by the assessment of causes of disorders, and ending by proposals of convenient repairing solutions in order to maintain the integrity of project in question. It is worth mentioned the high cost occasioned by this lengthy process (Sfar and Bouassida, 2001).

The aim of this paper is to sensitise under graduate students, during the preparation of end of studies projects, in civil engineering colleges, the importance of studying the pathology of case histories. This latter is strongly linked with geotechnical engineering especially for the explanation of disorders causes and their assessment.

At the National Engineering School of Tunis this kind of experience was undertaken, in 2007, by three couples of students who studied three case histories of pathology as related to two earth dams and a set of four engineering structures in Tunisia. The strategy above described was followed in view of the proposal of adequate solutions of reparation for each project. Focus is given on problematic soils as swelling and soft clays which are at the origin of main causes of disorders, in particular when combined with climatic effects and water movement.

In this paper a unique educational procedure is undertaken to treat three history cases dealing with the pathology of projects from the geotechnical viewpoint. The benefits resulting from such customised works, handled by future engineers, highlight the importance of such a tool of education associated with the importance of geotechnical engineering more oriented to soil mechanics aspects. Of course this type of collaborative work on case histories studies makes a stronger industrial liaison with universities. Indeed, the university is favoured by access on data base of big projects and practical know how. In parallel, industrials benefit from the update of advanced scientific tools and backgrounds more available and mastered by faculties. Therefore a truly beneficial transfer of knowledge, at different levels, takes place between universities and enterprises (Oliveira & Souto, 2007).

JOUMINE DAM CASE

The dam and its spillway

The construction of Joumine dam ended in 1983. The initial filling of reservoir took place from 1983 to 1986. The first full reservoir filling was reached after the 1987 floods. Under the permanent water-surface elevation, 90 m, the reservoir capacity is $130{\cdot}10^6$ m^3 and its submerged surface is by $660{\cdot}10^4$ m^2. The maximum reservoir water elevation adopted for the spillway design flood is 94.8 m. Joumine dam consists in a compacted earth embankment and an ungated side channel Spillway. The height of the embankment is 53 m and the crest elevation of the dam is 95.1 m. The spillway is located at the right abutment adjacent to the dam (Bel Hadj Ali and Louati, 2007).

The compacted dam material consists of diluvia-alluvial clay which provides the double function of stability and impermeability of the earth embankment. Its drainage is ensured by a riprap drainage blanket at the downstream portion of the embankment. This riprap blanket is made up of Maastrichtian limestone and argillaceous limestone. These materials were extracted from the excavation of the channel spillway which is equipped by a drainage trench and passive cables of anchorage. The argillaceous zone of the dam is connected to the drainage blanket at the downstream portion of the embankment by means of a reversed filter composed of two layers of crushed stones having each one 1 m thickness. The grain size distribution of crushed stones as soil of foundation ranges respectively for the first layer between 10 and 20 mm and for the second one between 40 and 80 mm. A similar filter is installed at contact of the riprap blanket with the foundation (Bel Hadj Ali and Louati, 2007; Coyne et Bellier, 2007).

The spillway is a reinforced concrete structure formed by slab elements and high retaining walls. The spillway was built on the calcareous formation located at the right bank. Since the rising of Joumine River flood is rapid and, in order to ensure a safe and quick evacuation of floods, an ungated side channel spillway with automatic regime was decided. This spillway is designed for a regularized flow of 2840 m^3/s. The foundation includes a tubular system filled by crushed stones to ensure the drainage of seepage water and, therefore, to prevent excessive uplift pressures. The slabs have a vault form with variable thickness varying from 0.7 m to 1.8 m. All slabs of the spillway are linked by water stop joints.

Statement of the problem

Upward movements were detected for some slabs of the spillway in 2001 (photo 1) (Coyne et Bellier, 2007). Recorded horizontal displacements, in 2006, indicated that the opening of slabs joint reached by 15 mm and upward displacement was 12 mm. These movements are still in progress.

Such disorders may have as origin, especially, sismicity of the region, the weight of slabs and the type of soil foundation in presence of water. Indeed, the dam is located in high seismic area where maximum horizontal acceleration reaches 0.2 g. Further, because slabs thickness ranges between 0.7 m to 1.8 m, differential settlement due to gravity may be occasioned.

In semi arid countries like Tunisia, the big climatic variations may generate significant change of water content in clayey soils. It results “swelling-shrinkage” cycles and, consequently, excessive uplift water pressures capable to generate uplifting of slabs as it was observed in the Joumine spillway case. Also, another potential fact is the dissolution of gypsum which may be responsible of observed damages. Then, analysing the seepage and pore pressure phenomena is necessary to highlight the causes of disorders.

The role of the drainage system is to avoid the percolations from the reservoir as well as from the natural slope therefore, under pressures and consequent uprising of slabs are avoided. The seepage-control system is composed by two draining trenches upstream-downstream with connection bank to bank each two or three slabs. Note that under the joints of the spillway slabs, no drainage system was installed contrarily to the majority of spillways. Due to the lack of recorded seepage flow data, the filling of the drainage system can not be proved (Coyne et Bellier, 2007).

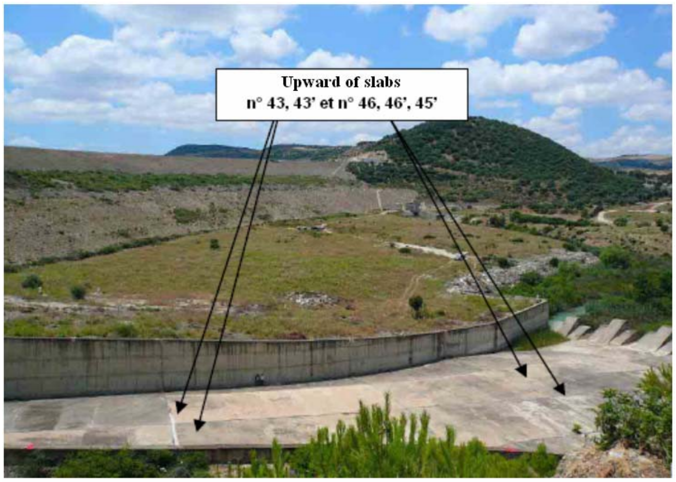

Photo 1. Low level view of earth dam focusing on disorders in slabs of spillway channel

Geological description

The side spillway is located in an area composed by Triassic terrains, upper Cretaceous and a stratified Palaeocene. The geological description showed, from upstream to downstream, after the white limestone of Higher Campanian where the spillway was installed, limestone and marls-limestone with rectified Campanien Maestrichien structure. Then were encountered successively a thin marl band, a Triassic band, another broader marl band, then again limestone (Figure 1) (Bel Hadj Ali and Louati, 2007).

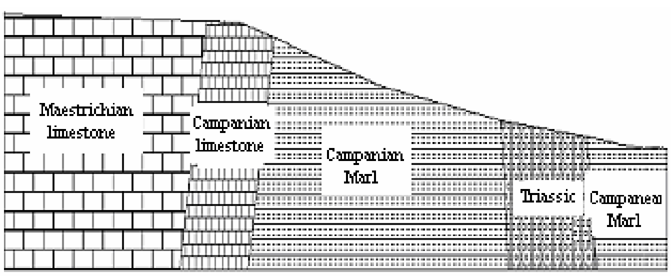

Fig. 1. Geological profile of the spillway foundation

From the mineralogical analyses it revealed the abundance of swelling mineral (Smectite) in the marls located in lateral bank - and most probably under – the slabs affected by serious disorders (Coyne et Bellier, 2007). These marls are highly plastic active clays. According to oedometric swelling results, the swelling potential of these clays is well pronounced. Triassic is few active clayey sand having a low potential of swelling. It is then concluded marls belongs to swelling soils category. It should bee kept in mind that swelling only occurs when expansive minerals are in presence of water. For this raison, focus on the flow pattern prediction, through the earth dam and more precisely under the spillway, is discussed in the next paragraph.

Studying seepage under the spillway

The dam is equipped with 70 piezometers enabling direct readings distributed over 10 cross sections. The recorded data from piezometers, between January 1985 and December 2006, have been used to draw the flow pattern at different dates (Bel Hadj Ali and Louati, 2007). While in non equipped zones with piezometers interpolation methods were carried out to estimate piezometric elevations. Software Surfer 8.0 (Golden Software, 2002) providing over twelve interpolation methods, each having specific functions and related parameters, was used as tool of prediction. The tested methods gave comparable average and standard deviation.

An example of flow pattern through Joumine dam is depicted in figure 2 which illustrates freely water flows under the slabs. Thus, it is essential to check the impact of these infiltrations on the stability of the affected slabs. Noticed that the equal potential lines are more spaced under the spillway and thus the hydraulic gradient is less important. Comparing the hydraulic potentials recorded along the spillway at different dates (figure 3), it appears that the hydraulic gradient remains constant from a year to another in the area crossing limestone and the marl. While passing from the marl to the Triassic, the hydraulic gradient decreases! In fact, the permeability of the Triassic is less important, the hydraulic gradient should increase. This constitutes the hydraulic signature which highlights the presence of preferential paths of flows. However, attributing this fact to an increase of permeability and, consequently, to a dissolution of gypsum it would be necessary to check the temporal decrease of hydraulic gradient in the Triassic. Thus, although it seems obvious to attribute the decrease in hydraulic gradients to the dissolution of the gypsum, it is essential to make sure, using experimental observations, the existence of preferential flow paths evolving in time.

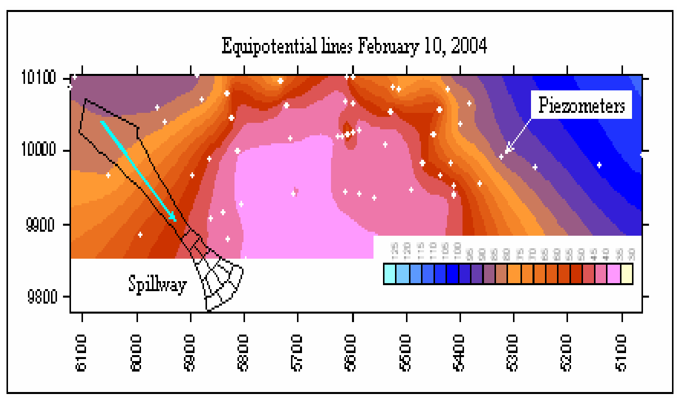

Fig. 2. Flow pattern within core dam

The numerical simulation of flow under the spillway has involved three longitudinal vertical sections: the first coincides with the spillway centreline, the two other sections being parallels to the centreline respectively on the right and left banks. This numerical simulation was conducted with SEEP2D which is a 2D finite element, steady state flow model (Brigham Young University, 1999). Using this model, confined and unconfined flow problems can be treated in parallel. Such possibilities fit well with conditions of the spillway of Joumine dam. Supplied with boundary conditions and soil properties, SEEP2D was used to determine head, flow distribution and seepage quantities under the spillway

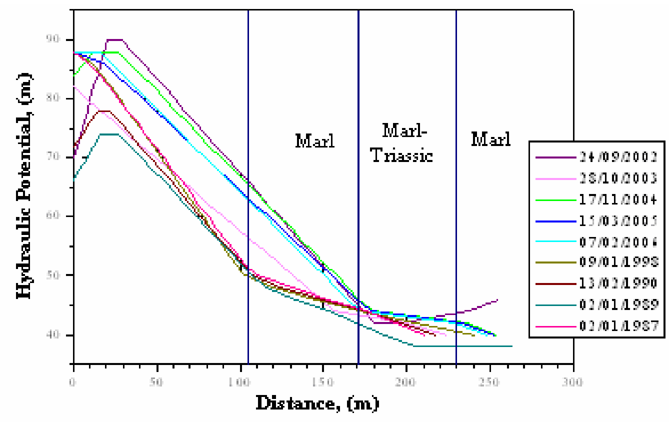

Fig. 3. Loss of water potential under the slabs of spillway

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Numerical simulation showed up full saturation of the soil under the spillway, excepting a minor part at downstream side. Consequently, water flow is up charged and leads to uplift pressure to be thoroughly quantified. The predicted outflow debit is of about 0.001 m^3/day. Hence, if lateral flow under the spillway is not taken into account the difference in hydraulic potential is fully transmitted to the slabs of spillway in term of destabilizing uplift pressures which lead to significant destabilising upward force.

The pore pressure variation as a function of distance between piezometers is given in Figure 4. Note that water pressure increases up to maximum value of 423 kPa within Triassic zone (Bel Hadj Ali and Louati, 2007). Maximum values of pore pressure are predicted at the interface marl - Triassic where disorders between slabs 44 and 46 are localized. Hence, the numerical simulation confirmed pore pressure as one of the main causes of disorders.

After the study of flow network it was concluded that the variation of hydraulic gradients per year, may lead to the swelling of marl or gypsum dissolution.

Numerical simulation of disorders of spillway dam

The numerical simulation using Plaxis software (Brinkgreve, 2003) permitted the localisation of critical zone critique of vertical displacement along longitudinal and cross sections of slabs. At Triassic_contact the slabs are subjected to an upward displacement, while in marl contact settlement are predicted. Such a result is in agreement with seepage study which showed disorders are due to high pore pressure at Triassic locations. Figure 5 illustrates the predicted vertical deformation (zoomed form) at the surface of slabs of the spillway (Bel Hadj Ali and Louati, 2007).

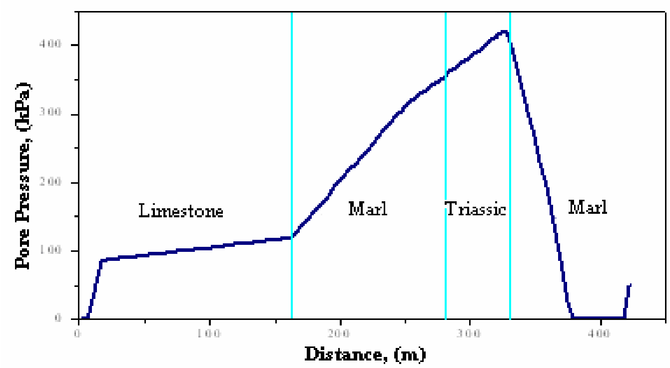

Fig. 4. Pore pressure variations along the spillway

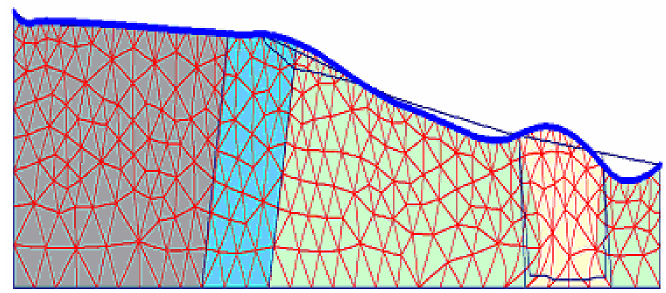

Fig. 5. Predicted deformation in surface along longitudinal section of spillway

Remedies to disorders of Joumine dam and practical recommendations

Remediation to disorders aims the stability from mechanical and hydraulic point of views. As primordial solution significant reduce of pore pressure under the slabs of spillway to prevent the evolution of observed damages on surfaces of slabs. Drainage is one of obvious and current solutions. Also the use of embedded anchors in rock mass combined by grouted cement slurry is the second technique to enhance the overall stability of lateral retaining wall (photo 1 above). Meanwhile after available geotechnical data it is not warranted the sufficient rigidity of rock mass to absorb tensile force induced within anchors of stabilisation. Such a technique is also recommended for in situ conditions and enables the reduction of soil permeability. As additional reinforcement procedure a transversal grouting under the slabs of spillway was agreed. This grouting line is executed at Maastrichian limestone location.

Then, drainage and grouting revealed the more convenient solutions to remedy the disorders of the spillway of Joumine dam. However, this decision needs an in situ supervision to conclude about the efficiency of suggested repairing solutions (Coyne et Bellier, 2007). As recommendations it was suggested to programme complementary boreholes with soil sampling for a better characterisation of geological and geotechnical parameters. Especially the activity and swelling potential of Triassic formation needs a thorough threaten. Further a more consistent survey of the variation of piezometric level around the spillway area should be recorded.

In situ plot tests, for passive anchorage grouted in the rock formation, are necessary as reinforcement solution for stabilisation, at long term case, of the slabs of the spillway .

SIDI SAÂD DAM CASE

The dam and its spillway

The dam of Sidi Saâd built on Zeroud wadi is intended for the protection of the plateau of Kairouan against floods, for the irrigation and for the recharging of groundwater table. Construction works occurred between 1978 and 1982. The controlled drainage area is of 8575 km^2. This watershed has given a peak flow of 17,000 m^3/s in 1969. The general design of Sidi Saâd has resulted, especially with a huge rooting flow capacity coupled with a remarkable spillway (Ben Messaoud and Hamdouni, 2007).

Under the permanent water-surface elevation, 270 m, the reservoir capacity is $209 \cdot 10^6$ m^3 and its submerged surface is $1710 \cdot 10^4$ m^2. The maximum reservoir water elevation adopted for the spillway design flood is 302 m. This great capacity is a characteristic of flood protection dams.

Sidi Saâd dam comprises, especially, a main earth dike of 70 m in height, a secondary dike of 48 m in height closing the collar at the right bank, and a side channel spillway made-up between the main dike and the collar one. The spillway (figure 6) comprises: (i) An intake channel by means of cut trench in limestone up 268 m elevation; (ii) An overflow weir at 290 m elevation discharging into a narrow channel width 60 m and 120 m in length; (iii) Five sluices at 270 m elevation; (iv) A concrete overflow spillway face of width 60 m finishing in ski-jump at 270 m elevation; (v) A second overflow spillway face of width 60 m finishing in ski-jump at 250 m elevation; (vi) An energy dissipation basin at the end of the spillway with tilted walls resting on the rock; (vii) A basin of restitution at 215 m elevation opened towards downstream to join the wadi Zeroud by a restitution channel protected over 50 m length.

Statement of the problem

The right bank wall of the overflow spillway face is anchored in the marl. It is divided into slabs separated by dilation-shrinkage joints. This wall is fitted with series of topographical landmarks, on upper and lower sides of the joints. Generally, lower landmarks are stable but upper ones still indicate a continuous movement oriented north (Coyne et Bellier, 2007).

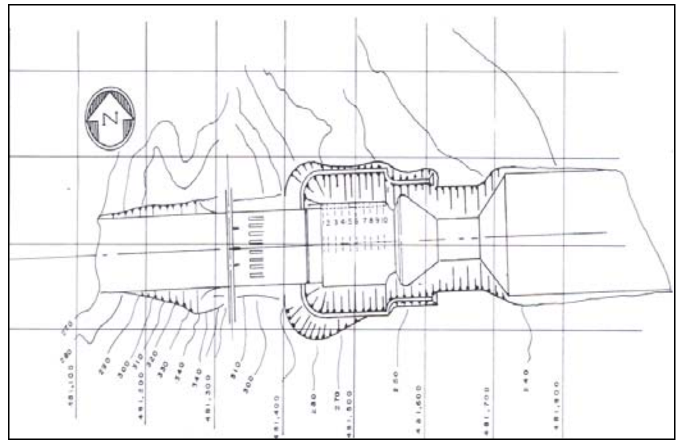

Fig. 6. Plane view of Sidi Saâd side channel spillway

The right bank wall of the spillway is highly tilted over its length, without having information about the eventual causes: either the creep of stiff natural slope, or possibly the swelling phenomena.

The tilting is characterized by an expansive deformation located at mid length and spectacular shearing ruptures at the extremities (photo 2). The maximum recorded inclination is about 400 mm, from which about 80 mm exist initially and 320 mm are the effective displacement: 220 mm which occurred during 16 years (since the opening of the excavations in 1980 until the commencement of topographical measurements). Remaining 100 mm were measured over the 11 years starting by end of 1995 till the end of 2006 (Coyne et Bellier, 2007). The rate of this effective displacement is respectively 14 and 9 mm/year in average, for each of the two periods. This deceleration of displacement is not enough significant.

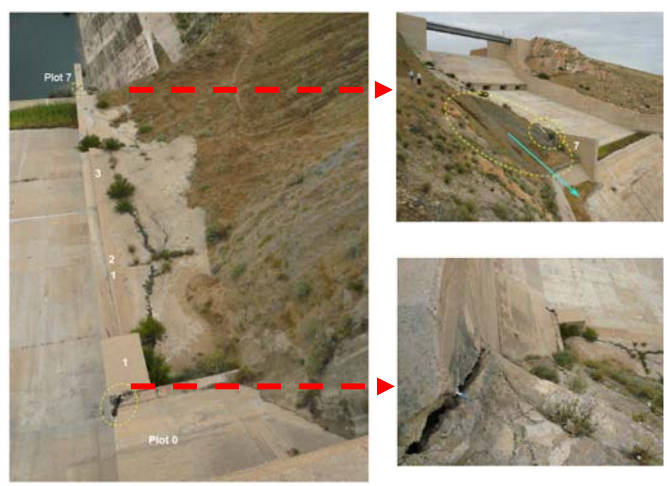

Photo 2. Tilting of the right bank wall of the overflow spillway face anchored to the marls.

The topographical landmarks, located at the bottom of the wall, do not tilt proportionally to the upper landmarks (Coyne et Bellier, 2007). One can think it not the question of block movement rotation; rather it is a lateral deformation of the wall (being not reinforced at the rock side) due to the marl active pressure.

Elsewhere, the rate of silting of the reservoir of sidi Saâd dam is very significant and generates a strong reduction in the capacity of normal reserve. The volume lost occasioned by sedimentation can be compensated by heightening the spillway crest.

Geological description

The geological formation is characterized by a notable dissymmetry: particularly the calcareous / marl contact is appreciably higher in the right bank than in the left bank. Thus, the top of the versant holds is self balanced in the left bank side. Contrarily, the right bank presents an extremely marl stiff slope which exerts high active pressure along the whole wall (Ben Messaoud and Hamdouni, 2007; Coyne et Bellier, 2007).

Marl soils have mechanical properties which make them particularly sensitive due to phenomena of instabilities (surface erosion, landslides). They are likely to change in volume because of the variation of soil moisture content. It follows the generation of cracks in the ground which greatly affect the stability of constructions built on such type of soils.

Studying the infiltrations

Devices for inspection of the main dike have been installed to record displacements, pore pressures and flows of percolation. Four cross sections gather most of the installed instruments: 39 terminals of observation, 2 columns settlement plates, 35 piezometers, 2 cells of total pressure. 12 piezometers among the 35 installed and the 2 cells of total pressure were not functioning since 2002 (Ben Messaoud and Hamdouni, 2007).

The piezometric measurements recorded since 1982 made it possible to draw the flow pattern at different dates (Ben Messaoud and Hamdouni, 2007). The examination of these flow patterns especially showed a convergence of current lines towards the right wall of the spillway in case of high water level in the reservoir. However, simulations with SEEP2D of a vertical section along the spillway highlighted the absence of under pressures: the flow remains unconfined regardless of the water level in the reservoir. The right wall of the spillway thus constitutes a barrier both for seepage water and streaming surface. Consequently, the phenomena of swelling are possible and it is essential to evaluate the presence of swelling minerals after making recourse to mineralogical analysis.

Study the stability of the right wall

The study of stability of right bank wall of the spillway and the prediction of surface displacements subjected to soil pressures were carried out using the Plaxis software. Considering the plane strain study and assuming, first, the materials obey to the constitutive law of Mohr-Coulomb, second, the soil is normally consolidated, the numerical simulation of two cross sections of the spillway allowed us to predict comparable results with the field observations. As illustrated by Figure 7 (Ben Messaoud and Hamdouni, 2007), the tilting movements are confirmed at the right bank wall of the spillway. Keeping in mind these movements started in 1995 and still continues to date.

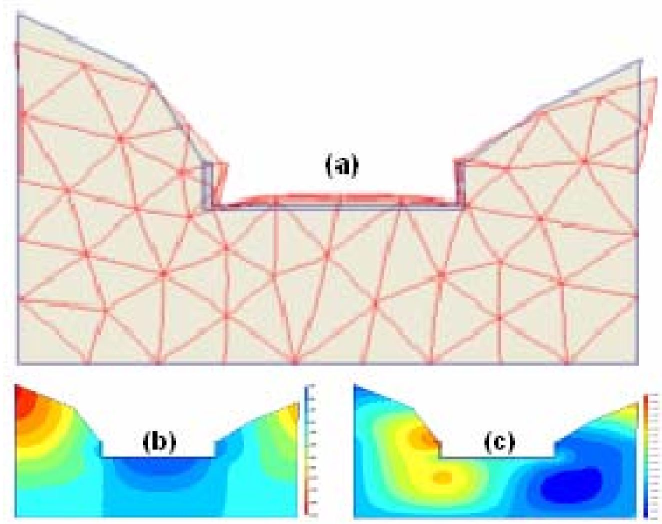

*Fig. 7.*Deformation (a), vertical (b) and horizontal (c) displacements

Remediate the disorders and practical recommendations

The depth of alteration in marls being a decisive parameter for the rehabilitation of the situation: some bore holes in parallel with soil sampling, followed by laboratory tests and mineralogical analysis for evaluation of the swelling potential minerals, are recommended. Anchored cables may be adopted to improve the stability of concrete wall. It is also recommended the set up of anchors and retaining devices and a protection by reinforced concrete projection of the new slope against deterioration (Coyne et Bellier, 2007).

Remediate the silting of reservoir

Most of the wadis in Tunisia carry in flood huge quantities of solids in suspension. The extent of the silting of reservoirs of dams is therefore a very worrying phenomenon. Concerning Sidi Saâd dam, the lost in volume due to silting, over 25 years, is by 78 10^{6} m^{3} (Ben Messaoud and Hamdouni, 2007). This volume represents about 37 % of the initial reserve capacity and corresponds to an average rate of filling of about 3.1 10^{6} m^{3} / year. One of the remedies for this unsatisfactory situation is to compensate the loss in storage volume by increasing the reservoir capacity. This increase can be achieved either by heightening the weir of the spillway, or by rising the threshold upstream of the intake channel. In all cases, the spillway must have a good hydraulic behavior even in the event of exceptional flood such as the project design flood. For this, in order to verify the spillway behavior, hydraulic simulations of the flood project rooting were conducted by using the HEC-RAS model (US Army Corps of Engineering, 2002). It should be reminded, when Sidi Saâd dam was designed, the heightening either of the weir of the spillway or the raising of the threshold upstream of the intake channel was taken into account. Such heightening does not affect the stability or the impervious role of the main and auxiliary dikes.

Modelling Water Surface Elevation along the spillway

To avoid the overtopping of the dike it is necessary to verify the outlet capacity of the spillway design flood. Then, the surface water elevation must be always lower than the maximum allowed water level. This implies to compute precisely the evolution of water profile during exceptional flood event. For this purpose, the spillway water profiles were calculated using the HEC-RAS model, first calibrated and then validated.

HEC-RAS model supports one-dimensional water surface profile calculations. This software is able to model a wide range of flow conditions. In steady case, the HEC-RAS model performs water surface profile calculations for gradually varied flow. Subcritical, supercritical, and mixed flow regime can be considered. Water surface profiles are computed using Bernoulli's equation in order to evaluate the energy variation from one cross section to the next using an iterative procedure. The loss in head of energy between two cross sections is constituted by friction and contraction or expansion losses. The friction slope at each cross section is computed from the Manning's equation. Contraction and expansion losses are evaluated from empirical equations (Djebbi et al., 2006).

The flows used as input for the calibration of the HEC-RAS model were characterized by a debit of 45, 273, 552, 682, and 1006 m^3/s. These flows were tested during experimental campaigns carried out on a scaled model. Simulations of these flows allowed to fix the friction Manning's n = 0.016 $m^{-1/3}/s$ for all the 52 transverse sections (Ben Messaoud and Hamdouni, 2007). The computed water depths were compared to the recorded ones. In all cases, the percent in error depth is less than 0.1%. The numerical results are acceptable and the calibrated model was used to simulate other higher flows. The spillway water profile obtained with a flow of 6940 m^3/s is depicted in figure 8.

The calibrated model was also used to study the influence of heightening of the weir on the hydraulic behaviour of the spillway. Several alternatives were tested. The simulations results showed that, considering only the hydraulic behaviour of the spillway, the two solutions (heightening the weir of the spillway, or rising the threshold upstream of the intake channel) are feasible. However, it would be necessary to carry out technical and economical studies in order to choose one of the two suggested solutions.

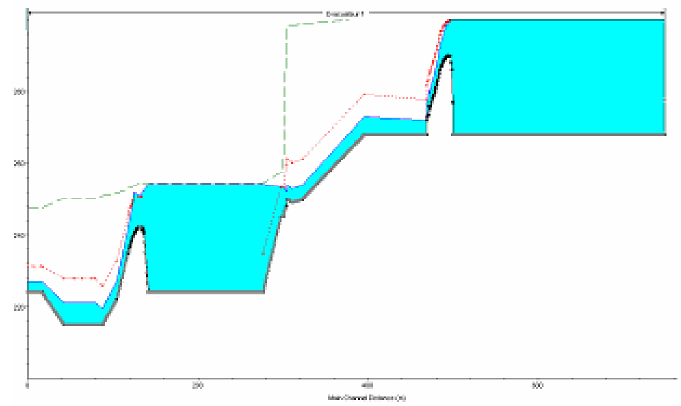

Fig. 8. Spillway water profile for a flow of 6940 m^3/s

ACCESS RAMPS TO ENGINEERING STRUCTURES ON RADES LA GOULETTE EXPRESS ROUTE

Description of engineering structures and occasioned disorders

In 1969, Chauffour Dumez contractor had built four engineering structures which link between the Tunis north lake and the navigation channel connecting La Goulette, Radès and Tunis harbours.

* The first structure, located at kilometric point PK 0+200, has 21 m length. It is composed by two parallel bridges carrying each one three independent reinforced concrete slabs structure overlaid by a pavement structure of 7 m breadth. As foundation, metallic end bearing piles have been designed along 22 m depth embedded in fine sand layer.

* The second engineering structure, located at kilometric point PK2 0+600, is a simple reinforced concrete slab of 14 m length, resting on two abutments founded on metallic piles in similar geotechnical conditions as for the first structure.

* The third engineering structure of length 21 m is identical to the first one above described.

* The fourth engineering structure of length 17 m is constituted by seven reinforced concrete buses, of external diameter 1.5 m, resting on a fill layer located at 2.5 m depth from pavement surface.

Disorders of embankments of access and bridges of Tunis La Goulette express route

The main difficulties which arise for the construction of embankments of access are:
- Short-term stability of the soft ground as related to bearing capacity verification.
- Long-term settlement of unimproved deep layers (depth greater than 30 m).

Observations and location of disorders

Access ramps of the four engineering structures are affected by visual disorders as cracks between approach and bridge slabs, opening of joints in pavement structures: the most pronounced is by 10 cm recorded for PK2 +600 and PK8 + 170 engineering structures. Similar disorders also were reported by (Bouassida et al, 2003).

The fourth engineering structure assumed as flexible structure, regarding the previous ones, behave identically as the surface terrain which settled due to primary consolidation process. Consequently, it followed the obstruction of buses due to different types of accumulated wastes. As a result the regeneration of water was not feasible due to the lack of entertainment.

Causes of detected disorders

From visual observations on the access ramps of all structures, settlement is apparently the main cause of disorders and caused damages as illustrated by photo 3 and 4. As a matter of fact, very significant settlements were recorded respectively of about 50 cm for PK 0+200 structure and about 40 cm for PK 0+600 structure.

Joints openings were also observed of about, respectively, 6 cm for PK 0+200 structure, and 10 cm for PK2+600 and PK8 +170 structures. Further, cracks due to contact between the edge span and approach slab were noticed.

Rotation of access slabs is due to differential settlements between embankment of access resting on high compressible soil and abutments founded on deep end-bearing piles foundation. The same pathology was detected between adjacent piers from which resulted concrete surface bursting favoured by steel corrosion.

Photo 3. Rotation of approach slabs followed by structure damages.

Photo 4. Rotation of piers

Interpretation of Geotechnical data

A geotechnical campaign was initiated in 1992 when disorders began to appear in the four engineering structures, Hydrosol (1992). Pressuremeter and sampling boreholes were conducted as in situ investigation, and laboratory tests have been executed on undisturbed specimens (Grain size, Atterberg's limits, oedometric and triaxial tests).

For each engineering structure the geotechnical profile has been identified with suitable soil parameters for each layer based results recorded from laboratory and in situ tests. Meanwhile the determination of some soil parameters was not realistic. As example from oedometric test results the compression index was not truly representative of soft layers, then the recourse to the well known Terzaghi & Peck's correlation: $C_c = 0.009(W_L - 10)$ enabled much realistic estimation.

Simulating causes of disorders

Plane strain calculations were carried out by the use of Plaxis software. Displacements and stress fields were predicted on the basis of Mohr Coulomb's constitutive law for soil layers. The numerical investigation included, especially, the primary consolidation evolution. Typical modelled structure is given in figure 9. The numerical simulation highlighted the differential settlement as difference between settlement under the embankment of access founded on soft layer and settlement under abutments build on piled foundation system.

The predicted differential settlement, s_d, well explained the disorders observed on access ramps. Other useful information was the prediction of remaining settlement of consolidation under each foundation element and the corresponding time evaluated by equivalent coefficient of consolidation of compressible layers (figure 10).

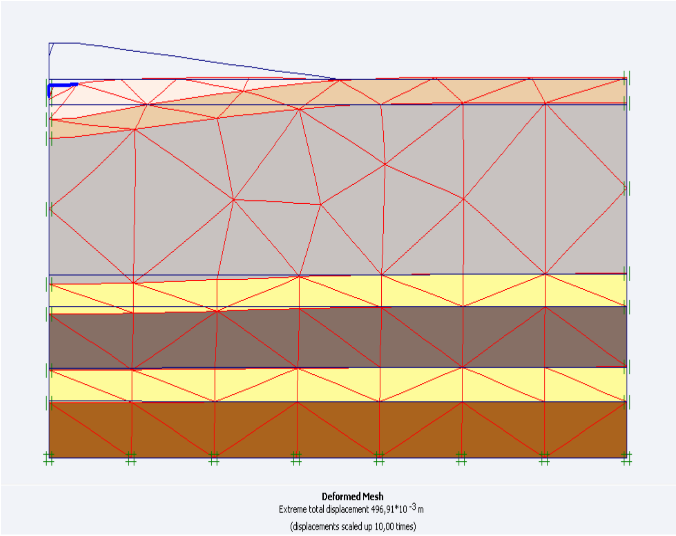

Fig.9. Vertical displacement by numerical simulation

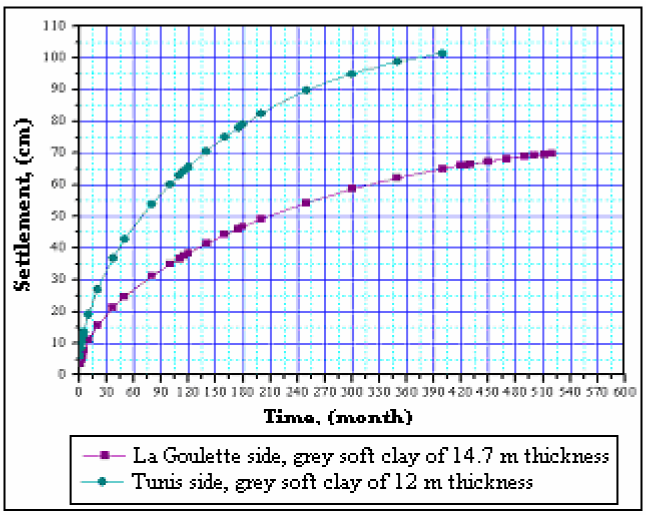

Fig.10. Settlement evolution in time: Structure KP8 + 170

As illustration, it was concluded for engineering structures PK0 +200 and PK 8 +170, as reinforced concrete structures, unallowable differential settlement (Table 1) when compared to limitation given by $s_d < L/1000$ where L equals the distance between two foundation elements.

Table 1. Comparison between differential settlements.

Engineering structure	Span length (m)	Predicted differential settlement (m)	Allowable differential settlement (m)
PK 0 + 200	22	0.33	0.022
PK 8 + 170	21	0.54	0.021

Suggested improvement techniques

To stop the evolution of disorders due essentially to continuous settlement of primary consolidation it revealed necessary the design of soil improvement (reinforcement) techniques aimed at substantial settlement reduction or acceleration of remaining consolidation. Then, two solutions were studied. First is the installation of rigid inclusions by means of metallic or concrete piles manufactured on site. Second are sands columns which play the role of vertical drains associated with light weight embankment material (unit weight equals 8 kN/m^3). The ground surface of improved soil is covered by a spreading mattress made up of drained sand to complete the outward drainage process from sand columns. This technique was finally approved because of moderate cost compared to rigid inclusions solution, (Bouassida et al, 2004).

Contribution of students

It comprises three key points. First is the interpretation of available geotechnical data and definition of the soil profile, including layers, geotechnical parameters and mechanical characteristics. Detecting the causes of disorders and explanation of their origins, via numerical simulation, is the second point. The third point is overall modelling of engineering structures and soil foundation combined with soil improvement (or reinforcement) techniques followed by practical recommendations.

Benefit for students

First most of the design methods related to bearing capacity and settlements estimation were applied. In this stage the handling of correlation due to insufficient data from geotechnical survey was greatly beneficial. Indeed, in soil mechanics course for undergraduate students the use of correlation is not a key point. Also the difference between Terzaghi and Menard methods for settlement prediction was highlighted and focus on differential settlement prediction from numerical simulation was very interesting. These latter enabled students to handle Plaxis numerical code dedicated to soil mechanics applications. Such a numerical tool used to be only practiced by up graduate students for research purposes.
Students became more familiar with recent advances in soil improvement techniques and designing piles by taking account of negative skin friction case.

CONCLUSIONS

Three case histories, aimed at pathology of civil engineering projects, were investigated by three couples of under graduate students for preparation of their end of studies engineering projects. Based on this common model of education, the paper discussed the procedure undertaken by students to come up with practical proposals of specific remediation after disorders observations, explanation of the causes of disorders and numerical simulation as assessment tool.

From the educational view point it appeared the strong connection between hydraulic and soil mechanics and geological engineering in civil engineering education.

Learned lessons from the pathology of case histories are quite important for beginner engineers when the study of new projects is tackled. This is an essential point for which more focus might be accorded in civil engineering education.

As prediction tools Plaxis and Seep2d software are quite practiced by undergraduate students for simulating various geotechnical purposes. These software were also handled during customized works programmed earlier during the education in applied courses as: hydraulic structures; engineering structure, soil mechanics, etc.

It is worth noticed the positive interaction between the industry and universities both for faculties and students.

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