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Structural damage in urban areas due to reservoir filling

Dommages structuraux dûs aux opérations de remplissage de réservoirs dans des aires urbaines

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ABSTRACT
Reservoir filling operations in hydropower or irrigation projects induce changes in regional flow and groundwater conditions, which may cause geotechnical, hydrogeology and water quality impacts in engineering projects. In special, projects where reservoirs reach important urban areas, rising water table may change soil matric suction and cause soil collapse and structural damage. During design phase, this is a most important issue, for design, construction and owner engineers to evaluate the extension and magnitude of the impacts or damage that will be imposed to buildings, roadways and utilities. This paper presents the methodology that was used in a case history in mideastern Brazil, of a 20,000 people urban area, located at the border of a reservoir lake that will be filled after the rainy season of 2004-2005. The paper presents the geotechnical characterization of the soils in the area of the project and their collapse potential. Also is presented the methodology to estimate structural damage and repair costs for the dam owner, to prepare an action plan for the post filling period. It is estimated that 99% of the buildings will present slight damage and approximately 1% will present moderate damage. To evaluate the average individual construction value, homes were inspected in their construction standards and apparent age, to estimate the order of magnitude of repair costs due to angular distortions that would be caused by soil collapse. Based on preliminary inspections to evaluate home conditions, the relative average repair costs were estimated in the order of 2.4% to 5.0 % of current construction value and total repair costs are expected to reach the range of US$ 300,000 to US$ 600,000.

RÉSUMÉ
Les opérations de remplissage de réservoirs dans le cadre de projets de production d'énergie électrique ou d'irrigation entraînent des changements dans la situation des nappes d'eau et des courants régionaux pouvant résulter dans des impacts géotechniques et hydrogéologiques, et liés à la qualité de l'eau sur des projets d'ingéniérie. Dans le cas particulier de projets où les réservoirs atteignent des aires urbaines importantes, la nappe phréatique montante peut modifier l'aspiration matrique, causant des effondrements et des dommages structuraux. Cette question est extrêmement importante lors des études quand les ingénieurs du maître d'ouvrage, de l'entrepreneur et du projet peuvent évaluer l'étendue et l'intensité des impacts ou des dommages susceptibles d'affecter des bâtiments, routes et utilités. Le présent travail décrit la méthodologie qui a été employée dans un projet situé en région centrale de l'Est du Brésil dans une zone urbaine habitée par 20 000 personnes et située au bord d'une retenue à être remplie après la saison des pluies 2004-2005. Ce travail présente les caractéristiques géotechniques des sols existant dans l'aire du projet et les chances pour qu'ils s'écroulent. Il décrit en outre la méthodologie d'estimation de dommages structuraux et des frais de réparations qui incomberont au maître d'ouvrage (barrage), en vue de l'élaboration d'un plan d'action pour la période s'ensuivant au remplissage. Il est estimé que 99% des bâtiments seront légèrement endommagés et que 1% environ subiront des dommages modérés. A fin d'estimer la valeur de la construction individuelle moyenne, les normes de construction des maisons d'habitation ont fait l'objet, ainsi que leur âge, d'inspection destinée à évaluer l'ordre de grandeur des frais de réparations dûs à des distorsions angulaires pouvant été causées par des affaissements du sol. En prenant pour base des inspections préliminaires réalisées pour évaluer la situation des maisons d'habitation, les frais moyens relatifs de réparation se sont situés entre 2,4% et 5,0% de la valeur courante de construction, et la totalité des frais de réparation, entre US$ 300,00 et US$ 600,000.

1 INTRODUCTION

Reservoir filling operations in hydropower or irrigation projects induce changes in regional flow and groundwater conditions, which may cause geotechnical, hydrogeology and water quality impacts in engineering projects. In special, projects where reservoirs reach important urban areas, rising water table may change soil matric suction and cause soil collapse and structural damage. During design phase, this is a most important issue, for design, construction and owner engineers to evaluate the extension and magnitude of the impacts or damage that will be imposed to buildings, roadways and utilities.

The objective of this paper is to present the methodology that was applied in a case history of evaluating potential structural damage and costs for an urban area. The area is located at the border of a future hydropower plant reservoir, to be filled by the rainy season of 2004-2005.

The activities in these studies were:

- Preliminary inspection of buildings and interview with owners to diagnose current situation, before reservoir filling;
- Geotechnical and hydrogeological investigations to characterize soil collapse potential and hydrogeologic conditions;
- Engineering analyses to evaluate degree and extent of potential problems due to reservoir filling, in special, structural damage and construction repair costs estimation.

2 PROJECT BACKGROUND

Golder Associates was retained in January 2003, to provide an evaluation of geotechnical risks associated to a densely populated area that would be affected by a future hydropower reservoir lake, in mideastern Brazil. The main goal of the study was to point out potential risks of structural damage on existing buildings and recommend an action plan to the client, to mitigate future claims related to reservoir filling, such as ground settlement and flooding areas.

The project is in a municipality of almost 20,000 people, located 40 km upstream from the dam. The most populated part of town covers two areas of approximately 500 m wide by 2000 m long, connected by a single 600 m span concrete bridge crossing the main river. The construction standards of the homes are typically, masonry buildings, two story high, 40 to 50 years of age and distributed at a maximum rate of 100 buildings per hectare. In average, lots are about 10 m to 15 m wide and 30 m long, with spacing between buildings in the range of only a couple of meters.

About 75 buildings were sampled and inspected to evaluate construction methods, structural design, cracking of the walls and current maintenance conditions. Eventually, some buildings exhibited poor maintenance standards and severe cracking, probably associated to poor construction method or localized settlement. In general, a systematic pattern that would indicate structural damage due to saturation collapse, in a particular part of town, was not observed during the preliminary inspection.

3 SUBSURFACE INVESTIGATIONS

Subsoil investigations were carried out by percussion drilling and auger holes in 27 points distributed along eight geotechnical cross sections, reaching a total length of about 250 m. Also, eleven investigation pits, were excavated in the right and left margins to collect undisturbed samples at an average depth of 5 meters, to run consolidation tests to determine settlement collapse potential. Grain size analysis and Atterberg limits were determined at regular intervals in the test pits. Infiltration tests and water table measurements were carried out in the investigation boreholes to determine soil permeabilities and groundwater flow directions.

The silty clay and sandy silty soils at the project site form the 5 to 10 m thick alluvial deposits and river colluvial terraces on both margins. The left bank has a wider and flatter area at a lower topography than the right margin. It is suspected that the left margin might have been a more recent river channel that evolved to the current position. Schistose rocks and residual soils form the hills surrounding the valley, in which the town has developed. Average water table depths are in the range of 3 to 5 m and permeabilities vary depending on the silt content, with an average value in the order of 10^{-4} cm/s to 10^{-5} cm/s.

4 HYDROGEOLOGIC CONCEPTUAL MODEL

Part of the homes that were built more closely to the river banks, at lower topographic elevations, were condemned and gave place to build the dikes on each side to contain the water. Originally at normal level, EL. 86 m, the river will reach EL 91 m after reservoir filling. The crest of the dikes will be at EL 94 m to protect against flooding events.

Before construction of the dikes, groundwater seepage within the alluvial and colluvial deposits of the valley are drained by the main river and its tributaries whose levels are mainly controlled by the hydrological regime. The construction of the dikes and reservoir filling will induce changes in regional flow and groundwater boundary conditions, as shown in Figure 1.

The groundwater table is basically controlled by the main river level. However, its position depends on the water balance between subsurface contributions of the system, in terms of subsurface recharge from the hills that surround the valley, I, evapotranspiration, E, water supply losses in the distribution grid, from leaking pipes, q_p, and eventual groundwater well use or eventual drainage system to control seepage, q_w , within the boundaries of the urban area of interest in the project.

With the increase in water levels contained by the dikes, a foundation seepage, Q, will occur from the reservoir, through the foundations of the dikes, until a new equilibrium is reached. Consequently, subsurface contributions will result in a regional groundwater table rise, Δh. In special, if in an area of potentially collapsible soils, rising water table may change soil matric suction and cause soil collapse, given as a percentage of the groundwater table rise, % Δh and depending on the magnitude of differential settlements, may cause structural damage in existing buildings and utilities.

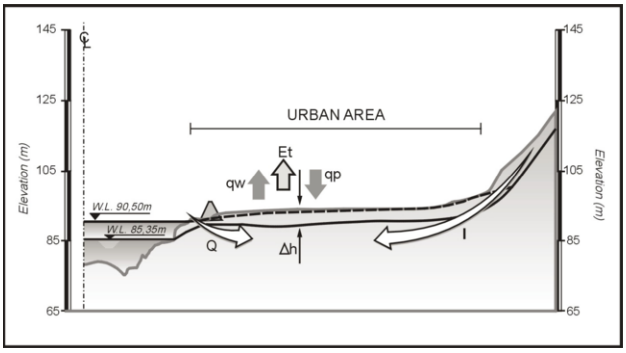

Figure 1. Hydrogeologic conceptual model – Surface and subsurface water flow contributions resulting in a regional groundwater rise, Δh.

5 GEOTECHNICAL ASPECTS

5.1 *Soil Collapse Potential*

Ferreira et al (2002) studied collapse behavior of natural unsaturated soils in several areas of Brazil, including irrigation projects of Petrolina and Petrolândia, located in the semi-arid region of northeastearn Brazil, where there was precedence of considerable structural damage in new and existing buildings. Thus, geotechnical characterization from these soils that were-included herein for the purpose of comparison and analyses.

Plasticity index results for the soils in the area of the project plot slightly below the A-line in the plasticity chart, with liquid limit, w_L, in the range of 22% to 63%, due to the typical soil deposit variability (Figure 2). The alluvial silty clay and sandy silty soils for the present case are represented by solid points in the activity chart, in the range of 0,35 to 0,40 activity index, slightly below the soils of Petrolândia, that presented a higher activity index, falling along the 0,5 activity index line.

Two samples were prepared from each investigation well, the first at natural water content and the other one saturated from the beginning of loading, with the purpose of determining the degree of collapse. The degree of collapse is defined from the two compressibility curves by $(\Delta H/H_i) \times 100$, where ΔH is the change in sample height due to saturation and H_i is the sample initial height.

The symbol lines in Figure 3 represent the degree of collapse-log σ'_v relationships for Petrolina and Petrolândia, while the ensemble of solid lines represents the soils of the project. The degree of collapse reaches a maximum between vertical stresses of 200 KPa to 800 KPa, beyond which collapse decreases.

For the present case, stress levels around 100 KPa, which corresponds to depths of 5 meters and where saturation is most likely to occur, are in the range of interest. For those stress levels the maximum degree of collapse is within the range of 4% to 5%. Degrees of collapse for Petrolina and Petrolândia are somewhat higher, in the range of 5% to 10%, for the same stress levels.

The ensemble of collapse degree curves also indicates that at some locations, there was little or no effect of saturation collapse. These points correspond to investigation pits located in areas of lower topography, that have been more susceptible to flooding events in the past. Samples collected at higher elevation alluvial terraces have exhibited higher collapse potential, probably because in these areas the soils have been more susceptible to infiltration and leaching and consequently, formation of a more porous particle arrangement.

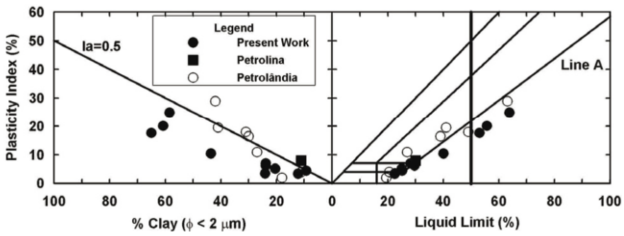

Figure 2. Plasticity chart and soil activity for the project area compared to other projects in Brazil (modified after Ferreira et al, 2002).

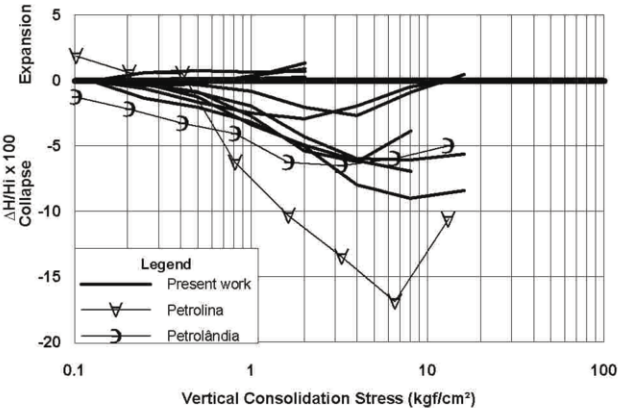

Figure 3. Degree of collapse – log σ'_v relationships.

5.2 *Settlement Analysis*

Settlements were evaluated by preparing maps for collapse potential, % Δh, estimated from undisturbed samples across the area and maps of changes in water table due to reservoir filling, Δh, estimated by a hydrogeologic numerical model (Visual Modflow 2000). The numerical model was calibrated with water table measurements in boreholes and water levels in creeks with the purpose of simulating the boundary conditions and subsequent water table rise.

As result of the analyses, collapse settlement was estimated along several geotechnical cross sections, across the area of the project, determining four zones of potentially decreasing levels of impact:

- Zone A – settlements between 50 to 100 mm;
- Zone B – settlements between 20 to 50 mm;
- Zone C – settlements less than 20 mm;
- Zone D – least impact.

In the right bank, a major zone with high impact or potentially high settlement (Zones A and B) was delineated, covering about 10 ha. Coincidently, this is situated in the central part of town, in a region most densely occupied and that conjugates high collapse degree of the soils and high water table rise.

The maximum levels of settlement are comparable to other projects in Brazil, such as Três Irmãos hydropower plant reservoir, where monitored maximum settlement collapse in the town of Pereira Barreto, due to reservoir filling, was in the order of 145 mm (Filho, 2002).

6 ESTIMATION OF CONSTRUCTION REPAIR COSTS

Angular distortions were estimated from the average slope of the settlement basin. Building damage was estimated following Boscardin and Cording (1989) approach, as function of angular distortion (Figure 4a). For example, for angular distortion between 2/1000 and 4/1000, structural damage would be moderate to severe, with appearance of small cracks, doors and windows sticking in their frames.

Marino (1985) developed a database to evaluate costs of repair in relation to cost of construction, due to coal mining subsidence in south central Illinois. This relationship is shown in Figure 4b, between the relative repair costs, RRC as a function of angular distortion. The relative repair cost is a measure of how significant is damage repairing in comparison to building a new structure. The higher the angular distortion, the higher the relative repair costs and beyond certain levels of angular distortions, RRC can rapidly reach significant values. For example, above 4/1000 the building may be severely damaged and relative repair costs may imply in values of 60% to 80%, which is almost the cost of a new construction. Roberds (1993) has applied a similar approach using the second relationship in Figure 4b. Other references relating repair costs and levels of angular distortions, more qualitative than the ones indicated, can be found in the literature (National Coal Board, 1975).

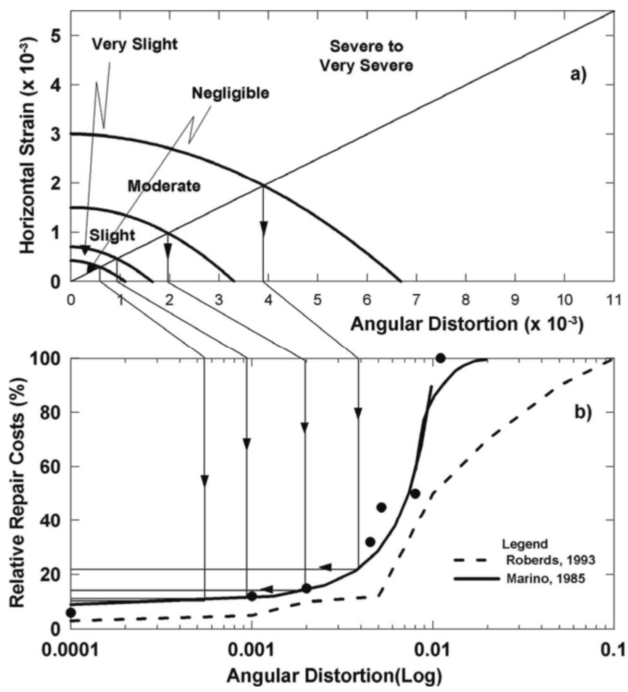

Figure 4. Structural damage and relative repair costs relationship.

In the lack of a local database, it was decided to use the relationships presented in Figure 4 to estimate structural damage and relative repair costs. This was carried out to give the dam owner a preliminary estimation of the order of magnitude of economic impacts for the project. With the collapse settlement troughs for the cross sections in the area, the distribution of structural damage and the distribution of relative costs were estimated. The results are summarized in Table 1, showing that the majority of structural damage would be minor to slight, with RRC between 2% and 10%. Only a small percentage of homes

(1% to 2%) would have moderate damage, with RRC between 10% and 14%.

Table 1 - Estimated structural damage and repair costs

Structural Damage	P[damage |collapse] (%)	Relative Repair Cost - R.R.C. (%)	f x R.R.C. (%)
Negligible	83	2 a 4	1.7 a 3.3
Very Slight	12	3 a 10	0.4 a 1.2
Slight	4	4 a 11	0.2 a 0.4
Moderate	1	10 a 14	0.1
Severe to Very Severe	0	Above 11 to 21	0
Total			**2.4 a 5.0**

To estimate the weighted average cost of repair for a single home, the distribution of the probability of damage given collapse, P [damage | collapse], was multiplied by the distribution of RRC. The average is between 2.4 % to 5% of construction costs, or approximately US$ 300,00 to US$ 600,00 per home, to repair structural damage. Considering that approximately 1,000 homes will have to be repaired after the impact of reservoir filling takes place, repair costs are expected to reach the range of US$ 300,000 to US$ 600,000.

7 CONCLUSIONS AND EXTENSIONS

The studies presented herein aimed at the evaluation of potential structural damage and repair costs in an urban area located at the border of a future dam reservoir. A geotechnical investigation program was carried out and repair costs were estimated to give the dam owners a preliminary order of magnitude of economic impacts for the project.

The main set of recommendations that were subsequently made, included:

- To carry out a more detailed through inspection to document current building structural conditions before reservoir filling;
- To implement a monitoring program to observe groundwater levels and settlements within the project area.

These would allow gathering a local database to give more credence to future analyses and more input for mitigation measures.

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