# Crest sinkholes related to the collapse of loose material upon wetting

## Cônes d'affaissements, en crête d'ouvrages zonés, reliés à des tassements internes de matériaux lâches lors de la saturation

B.BONCOMPAIN, Consultant/Sociéte d'énergie de la Baie James, Montréal, Québec, Canada
J.J.PARÉ, Shawinigan Lavalin Inc., Montréal, Québec, Canada
J.LEVAY, Hydro-Québec/Société d'énergie de la Baie James, Montréal, Québec, Canada

SYNOPSIS: During first reservoir filling, three sinkholes (2 to 3 m deep) developed along the crest of two large embankment dams of the La Grande Complex, Phase I. Their occurrence is clearly related to the collapse upon wetting of localized areas of poorly compacted unsaturated materials adjacent to the instrumentation riser pipes. Instrument data and test results give a clear picture of the in situ progressive collapse of the soil as well its magnitude.

## INTRODUCTION

The reservoir filling of La Grande Complex Phase 1 followed the construction of about 220 earth and rockfill embankment dams and dykes. The material used for the impervious zone of all these embankments consists of a broadly graded non cohesive till material (Paré and al and SEBJ).

## CREST SINKHOLES

In October 1983, at the end of the LG 4 reservoir filling, a sinkhole appeared on the crest of the QA-8 dyke downstream of the center line involving some 30 $m^3$ of material (Fig. 1). The dyke, founded on bedrock, is designed with a central till core and granular filters and shells. The sinkhole was located on the highest section (92 m) of the embankment, near the edge of an instrument island. A sharp reaction of the piezometers (2 m rise) and of the inclinometer (Fig. 2) indicated that the collapse affected the core to a depth of 55 meters below the crest.

Although similar sinkholes occurred with the same type of glacial till over untreated fissured rock foundations at the Churchill Falls Project (Seemel and al.), such an internal erosion process was rejected after analysis as the cause of the QA-8 sinkhole. As no deficiency was found in the quality and placement procedure of the filter, the most probable cause was the one related to the lack of compaction of partly saturated material which would have collapsed upon wetting due to reservoir filling. The location of the sinkhole in the instrument island was a very strong clue to the relationship between the phenomena and its cause.

Following this event, an investigation by dynamic penetrometer testing was carried out in 1984 in order to better define the chimney geometry of the sinkhole and to check islands elsewhere on the Complex. During this campaign, at LG 3 the reservoir was rising and two sinkholes occurred on dyke TA-10 at the location of two instrument islands, upstream of the embankment center line. Although there was no information supporting the fact that the material was in a looser state, it was clear that the collapse occurred in a zone where no field density measurements were carried out on the instrument islands.

These findings showed clearly, that the cause of the sinkholes or large differential settlements upon wetting of the instrument islands was related to the following:

Figure 1. QA-8 dyke - Crest sinkhole and raiser pipe.

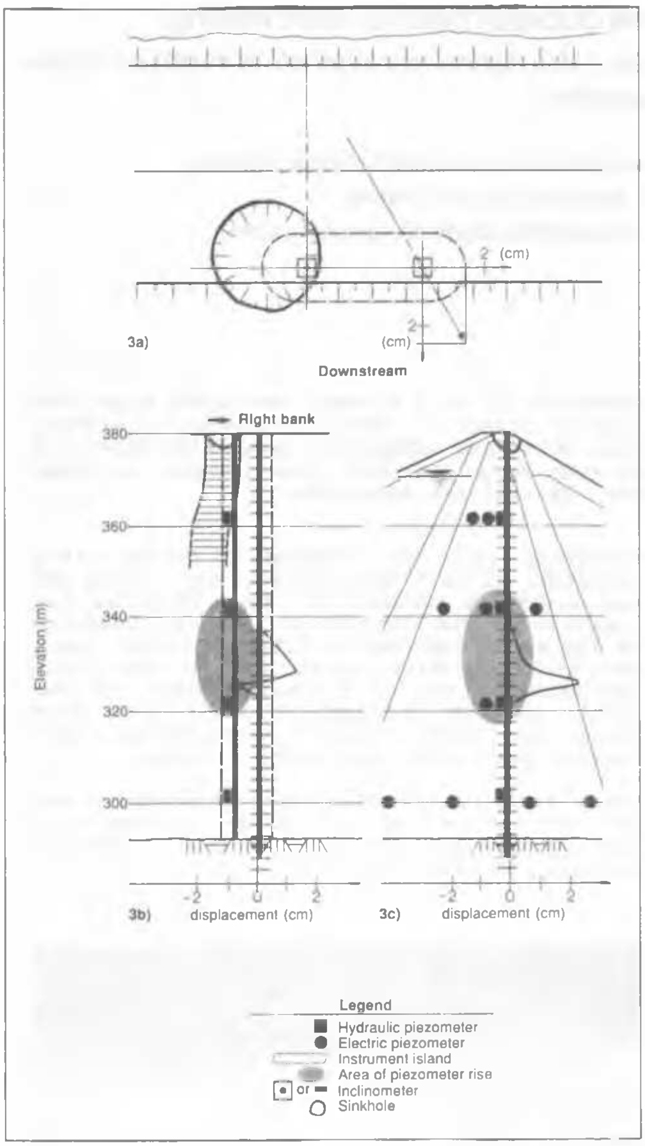


Figure 2. QA-8 Sinkhole - Instrument Reaction: Plane view, Longitudinal section, Transverse section.

- lack of compaction of the instrument island (TA-10-sinkhole);
- lack of compaction at the periphery of the instrument island, especially in the zone where the spool rack for the electrical piezometer cables was systematically located during embankment construction (QA-8 sinkhole);
- lack of compaction while backfilling a trench, done to replace an instrument damaged during placement (QA-1 dyke).

The first two examples occurred for all the instrument islands of each of the two embankments constructed during the same year, emphasizing the placement deficiency locally of one construction season.

Recently, a sinkhole appeared along the crest of the LG 2 Main Dam, 7 years after the end of first reservoir filling and lead to the same conclusions.

FIELD DATA - DYKE TA-10

The instrument data which best illustrated the collapse process was obtained from the TA-10 dyke inclinometer (Fig. 3). This embankment, with a till core and granular shoulders, has two instrument islands. The protection islands were built over a 1.5 m radius around the instruments, with the same material as the surrounding till but with the following modifications: the gradation size limit was 75 mm, the compaction was to be made in thin lifts of 150 mm using a vibratory plate or small roller. In addition, a finer material (max 19 mm) was placed on a 150 mm radius around the inclinometer tube to limit damage caused by coarse material along the inclinometer tube. The instrument islands were built one meter above the surrounding fill, offering a good protection for the instruments against heavy construction equipment.

Analysis of the field quality control data indicates that for both instrument islands, no compaction testing was carried out between elevation 207 and 213 m or above 222 m, i.e. for the construction carried out in 1980 and at the beginning of 1981. Water content determination, which was carried out over the same period, indicates a material placed generally drier than the Optimum Moisture Content by some 1,5%. However, compaction control testing of the surrounding core shows that the till was compacted as required.

During construction, the settlements measured by the inclinometer (at the base of rigid, 3 m long sections) were in good agreement with the measurements taken at other embankments of the Complex (Verma and al). The settlements were representative of the surrounding mass till for a partly saturated, well compacted, material.

When reservoir filling started, the inclinometer showed a rather peculiar behaviour (Fig. 3):

- The first wetting of the core occurred in 1979 during the construction period. This affected the base of the core above the rock foundation, between elevation 207 and 213 m and a settlement of 90 mm occurred while the overlying material between elevations 213 and 222 m settled by much less and never collapsed (penetration testing in 1986 showed the existence of arching).
- Inclinometer data taken between June 1981 and June 1982 shows the progressive collapse of the column accompanied by a loosening of the upper part, during reservoir filling (Fig. 4). The collapse and reconsolidation of the collapsed material reach a strain equal in magnitude to 5% . The rupture of the inclinometer indicated possible voids of 80 cm in the top of the island.

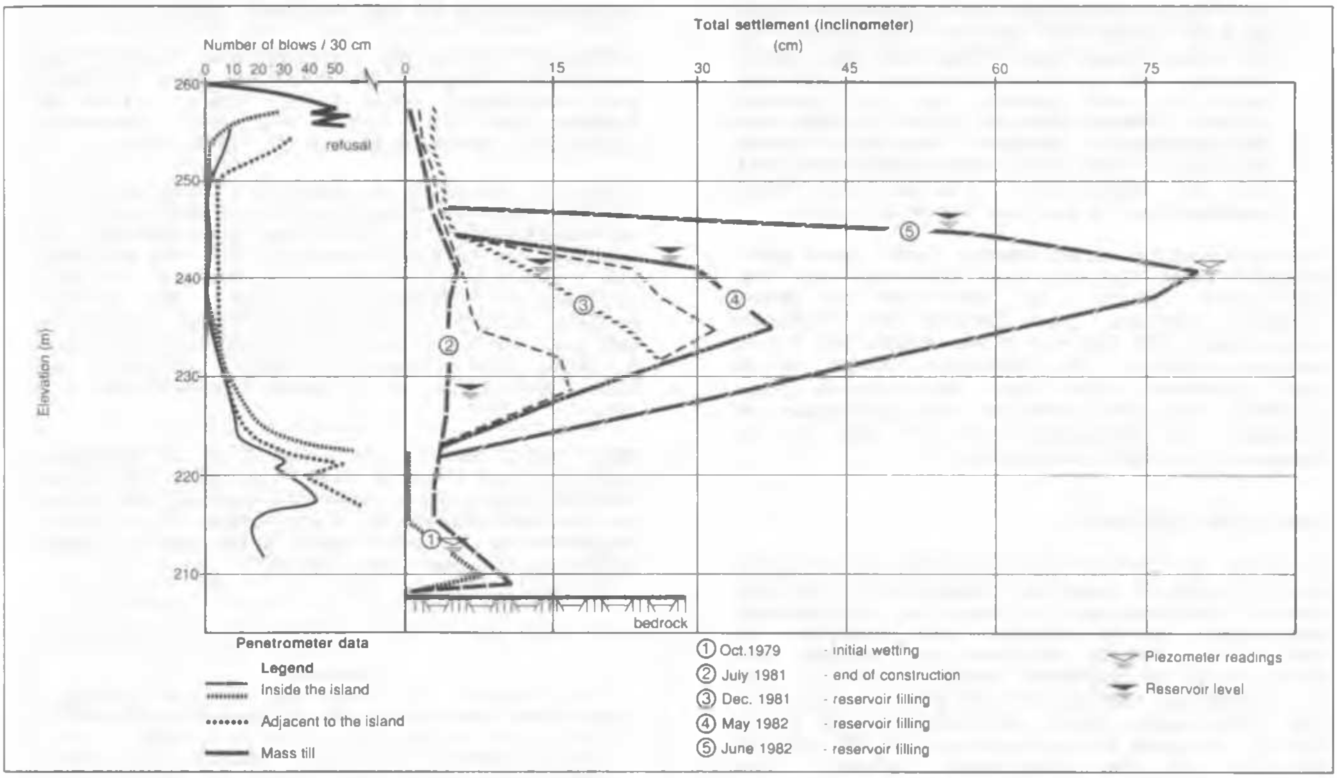


Figure 3. TA-10 - Penetrometer and Inclinometer data.

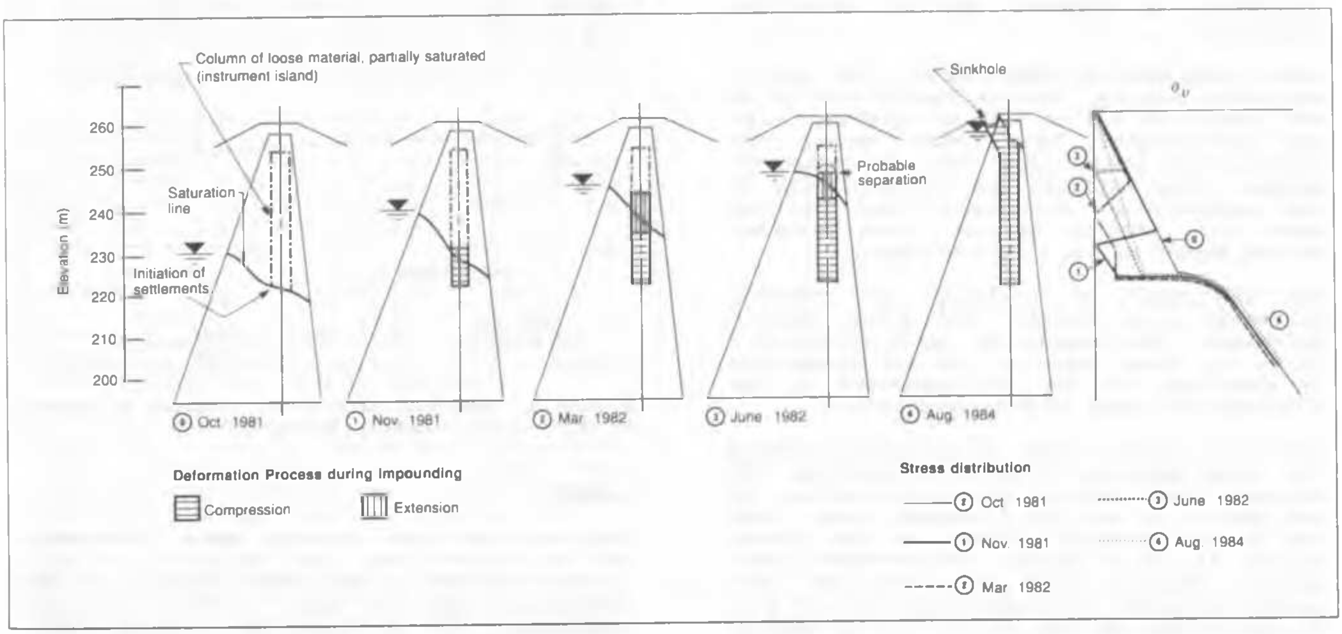


Figure 4. TA-10 Dyke - Schema of Movements and Stress distribution upon wetting.

- Five dynamic penetration tests where done in 1984 at TA-10, one as a reference in the mass till, away from the instrument islands, one in the piezometer island and three in and around the inclinometer island. These results (Fig. 3) show for the instrument island, a radically lower resistance then the surrounding mass till and a resistance profile in good agreement with the inclinometer data.

The surrounding penetrometer tests show good evidence that the collapse affected only the instrument island. At the time of penetrometer testing, just before the sinkhole occurrence, the top 4,5 m was supported by an arching effect. The sinkhole volume is in good agreement with the inclinometer settlement data and confirm the magnitude of collapse or settlement of 1% and 5% as measured in other locations.

LABORATORY TESTINGS

In order to verify the magnitude of collapse upon wetting of material compacted on the dry side of optimum and to check the influencing parameters (water content and density), a laboratory testing program was carried out using a 100 mm diameter oedometer cell. The till material tested was the fraction passing the 5 mm sieve which corresponded to about 75% of the mass till gradation and 85% of the material of the instrument island. The results of the maximum and minimum density measurements, show a very large difference in the void ratio (1.0 for the minimum density and 0.3 for the maximum density) which is characteristic of such a broadly graded material.

Results of the laboratory testing program, (detailled in Lefebvre and al) show the following:

Under progressive compression, the partly saturated samples, with a density of 94 to 98%, settle by 0,5 to 0,8% in agreement with the inclinometer data taken during the construction stage under the same range of stress. This confirms the representavity of the construction inclinometer data for the mass till, whether or not loose material exists around or near the instrument.

The settlement or collapse upon wetting increases while density and water content decreases. Settlements can reach values of 3 to 5% for loose material and are comparable in magnitude to the ones measured in the instrument islands as described before.

The total strain under progressive loading for loose material indicates a potential for collapse under wetting and consolidation, if one admits, as will be discussed later, that the loose material placed in the column island is in a highly understressed condition. Material with less than 90% compaction exhibits a collapse potential of 3 to 5% and values as high as 10% can be reached for a very loose material.

INTERPRETATION OF THE COLLAPSE MECHANISM

Although laboratory testing was limited and relatively simple, the results, due to their good agreement with field data, allow an explanation to the collapse mechanism especially in the case of the TA-10 dyke.

Figure 4 presents a schematic interpretation of the instrument protection island behaviour as the reservoir filling was progressing. By assuming no lateral movement, one can estimate the variation in vertical stress as the soil collapsing phenomenon develops. The corresponding stress state path for various parts of the collapsing column is presented on Figure 5, using the oedometric results of dense and loose materials at a water content of 6.6% (Wopt - 1,5%)

This simplified interpretation is in agreement with the inclinometer data and with the penetration resistance measured before and after or before sinkhole occurrence. It fully supports an in situ soil structure collapse magnitude in the order of 5%.

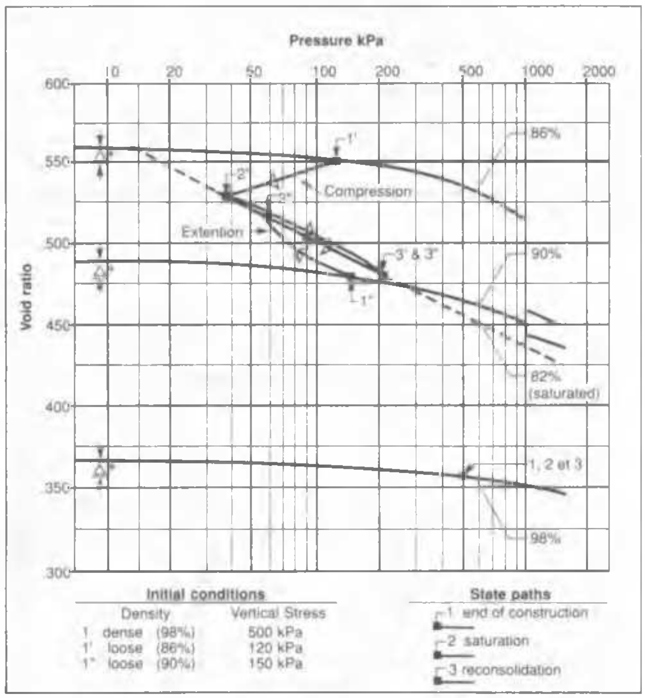


Figure 5. Compression Curves (Samples prepared at w: = 6.6%) - State Paths.

COMMENTS

From what has been reported above, it should not be deduced that the existence of instrument islands or even the presence of the instruments are the cause of such collapse phenomena. On the James Bay Project, most instrumentation islands have been built satisfactorily. Furthermore, fill embankment construction has been carried out under high standards of placement and control and embankments as a whole behave very satisfactorily. Therefore, the local deficiencies, which did not endanger the structures themselves are of interest for the following reasons:

- They confirm that all partly saturated materials will collapse upon wetting if they are not well compacted; collapse will be greater for relatively drier material. Although this statement may be evident to many, the occurrence of the sinkholes demonstrates that even in so called well designed and well constructed embankments, such deficiency may occur.

- Such a collapse mechanism may have contributed significantly to many other incidents which may have been attributed to hydraulic fracturing. In the present case, the deficiency in compaction was not easy to demonstrate as detailed evidence of such deficiencies are seldom found in "as built" reports. The reported phenomena (wetted column) could be related to wet seams often associated to hydraulic fracturing.

- Magnitude of collapse is higher for broadly graded loose materials such as till than for more uniform material and one may suppose that such phenomena may occur in a filter but with a reduced magnitude. The authors believe that proper compaction of embankment material is a strong priority in all cases, even though some arching may develop.

- Instrument data can be greatly influenced by the surrounding material. Phenomena such described above, could explain piezometer levels which do not reflect the general embankment behaviour but local deficiencies in their installation.

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