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The Friant-Kern canal : a forgotten example of lime-treated structure in hydraulic conditions

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The Friant-Kern irrigation canal is located along the foothills of the Sierra Nevada, southeast of Fresno, California. It has a length of approximately 240 km, and was designed for a maximum waterflow of 150 m³/s. It was built in the late 1940's using highly expansive clay; the earth-lined sections have 2:1 slopes, a bottom of 17.7 m width, and a top width of 45 m. Since the construction period, the earthen banks have suffered periodic damage from cracks, slips and slides. Concrete –lined sections also show failures due to the swelling of expansive soils.

In the 1970's, the Bureau of Reclamation decided to repair approximately 13.5 km of failed sections using lime treatment of clays taken from the banks of the canal. The methodology and devices used for the quicklime treatment are explained in the paper. The treated clay was replaced and compacted by a sheep-foot roller, to achieve a typical thickness between 60 cm (top and bottom of the canal) to 1.2 m (slopes).

The observed performance after 12 years [Gutschick, 1985] and 35 years of service (visit in 2010, and testimonial of maintenance department) is very relevant. No new slips or slides have been observed since the rehabilitation works in the 70's . Despite the fact that the lime-treated soil has been in constant direct contact with the waterflow, without protective cover, only minor erosion was observed along the waterline. The small holes in the surface of the banks were caused at the construction stage by the loss of "clay balls", i.e. small lumps of clay that were not completely mixed due to the poor efficiency of the mixing devices used at this time.

In addition to the achievement of the initial objective, which was the mechanical stabilization of the banks of the canal, the Bureau of Reclamation reported other advantages of the lime-treatment procedures: the cost savings during the repair works, and the very limited maintenance operations in the lime-treated sections in comparison with others (e.g. concrete-lined sections).

Key words

lime treatment, erosion resistance, stabilization of slopes, durability

I INTRODUCTION

Lime stabilization of soils has been a widely used technique since the mid-1940's for stabilization of clay-gravel base materials and later fine graded soils for roads, highways, airfields, railroad beds, etc.[Little,

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1995] The technique has also been used for decades in Europe to improve and stabilize silty and clayey soils for the same kind of earthworks applications.

An uncommon and spectacular application is the use of lime-treated soils for hydraulic earthen structures, i.e. structures where the lime-treated materials could be partially or completely submerged, such as canals, levees, dikes, earth dams, reservoirs...

The use of this technique came from three main reported benefits of lime treatment: [Gutschick, 1978] (1) preventing softening while underwater (the lime-treated soil doesn't revert to mud), (2) preventing the leakage and (3) resisting erosion from flowing water. The reduction of shrinkage and swelling movements of high plasticity index soils (heavy clays) after lime treatment, is also an important benefit for the reduction of the occurrence and development of cracks.

Used by several American and Australian authorities and offices for hydraulic earthworks restorations or reinforcement since the 1970's, [Perry, 1977; ANCOLD, 1978; Gutschick, 1978; Gutschick, 1985; Knodel, 1987; Fleming, 1992; USBR, 1998; Stapledon, 2005; USACE, 2010] the soil treatment by lime for hydraulic purposes seems to have been forgotten or even unknown, in Europe. For this reason, the Lhoist Group decided in 2005 to lead a series of important research programs in order to improve the conditions and procedures for the lime treatment, material placement and compaction steps, and also establish the relevant properties of materials for their use in earthen structures in contact with water. The presentation of the main results of those research programs is the topic of another paper of ICSE-6 Conference. [Herrier, 2012]

The Friant-Kern irrigation canal in California has been probably the best testimonial for the relevance and efficiency of soils lime treatment for a hydraulic use. Located along the foothills of the Sierra Nevada Mountains southeast of Fresno, this canal has suffered since its construction in the late 1940s from cracks, slips and slides caused by shrinkage and swelling phenomenon of the heavy clayey soils used for its construction. Those failures began soon after the initial construction and have plagued the canal operations ever since [Garver, 1987]. Failures have occurred in sections built entirely of earth, and also in sections built of earth and lined with concrete.

The office responsible for the canal is the Bureau of Reclamation of the U.S. Department of the Interior. The Bureau of Reclamation (USBR) acts for the development and conservation of the Nation's water resources in the Western United States, and has constructed a great number and variety of hydraulic structures for water storage and conveyance, using a variety of construction techniques and materials, but primarily soils.[Howard, 1976; Knodel, 1987]

II FRIANT-KERN CANAL DESCRIPTION, SOILS CHARACTERISTICS AND PROBLEMS

[Howard, 1976; Knodel, 1987]

The Friant-Kern Canal is approximately 240 km long was constructed between 1945 and 1951. It starts below the Friant Dam, 40 km northeast of Fresno, California, and follows the east side of the San Joaquin Valley for 240 km to its southern terminus in the Kern River near Bakersfield. The canal delivers water to more than 400.000 hectares of irrigated farmland in southern California. The normal capacity of the canal is 115 m³/s at the beginning, and gradually decreases to 57 m³/s at its end. The canal averages 5.3 m in depth with a bottom width of 11.0 m.

About 87 km of the canal traverse an area of heavy montmorillinitic clays (Porterville formation, PI from 35 to 55) [Gutschick, 1985]. Those soils exhibit significant volume change, namely expansion and shrinkage, according the weather conditions and moisture content. The volume changes have been identified as a serious problem and are significantly greater for compacted soil than undisturbed soil. Below the water level, the compacted soil expands due to water absorption and can lower the densities and strength; above the water surface, shrinkage occurs and deep cracks appear which are a preferred pathway for water, and consequently loss of shear strength of the blanket. [Knodel, 1987]

The typical slough slide can be defined as a shallow slide whose maximum depth to the slip plane varies from 1.2 to 2.5 m, and whose failure is triggered by heavy rainfall after an extended period of weathering.

The slides occur primarily between the riverside crown and a point midway down the slope, and can reach more than 100 m in length along the levee. [Fleming, 1992]

Of the 87 km of canal built with Porterville clays, 37 are earth-lined and 50 concrete-lined. Failures have occurred in both sections, and began only 3 years after construction. Cracks, sliding and sloughing of slopes have been a continuing, expensive maintenance problem. In the concrete-lined sections, the swelling of the clay foundation caused many of the concrete panels to crack with “pop-outs” of blocks or even slides of entire concrete panels (Figure 1, picture taken in November 2010).



Figure 1: Concrete lining failure on the Friant-Kern canal (Nov. 2010).

The concrete pop-outs and slide of the panel is due to the swelling of expansive clay, material used for the embankment. A temporary protective gravel layer was placed at the junction with remaining concrete panels.

III CONVENTIONAL REPAIR TECHNIQUES

The normal repair technique for the concrete-lined areas has been, after a dewatering step, to remove the broken concrete pieces and the loose embankment, compact imported suitable earth in place and place new concrete lining. The problem with that technique was the availability of suitable soils, and/or the transport costs for bringing the materials to the jobsite. In the earth-lined sections, the sloughed earth was typically replaced by gravel or rock, this procedure being accomplished with the canal still full of water. This technique is described as not entirely successful for several reasons: it is not permanent, it is unsightly, it degrades the hydraulic properties of the canal (water flow), and finally may result in a thinner section of impervious embankment. [Garver, 1987]

To control the deterioration of the Friant-Kern Canal, some slopes were flattened from 3:2 to 2:1, but remained unstable. An electrochemical method was even tested in the 50's to stabilize the expansive soil, but was judged as inefficient and not economically feasible.[Howard, 1976]. After these inefficient or unsuitable repair solutions, the Bureau of Reclamation (USBR) decided in 1972 to use lime treatment for restoration of damaged zones.[Howard, 1976; Gutschik, 1978 & 1985; Knodel, 1987]

IV ESTABLISHMENT OF LIME REPAIR TECHNIQUES

IV.1 Effect of lime on soils [Howard, 1976; Herrier, 2012]

Adding lime to silty and clayey soils has important immediate effects for earthworks: reducing the moisture content (if quicklime is added), improving the soil workability and increasing the soil cohesion.

The improvement of the soil workability is the consequence of the flocculation of clay particles and the reduction of plasticity index. The lime-treated soil becomes more friable and coarser than the plastic, wet original material. The improvement of cohesion and shear strength comes from the bonds established in compacted lime-treated materials. If a sufficient amount of lime is added, the available lime reacts with water and dissolved silica and alumina from the soils to form, through so-called "pozzolanic" reactions, new bonds with soil particles increasing cohesion and mechanical strength with time.

A spectacular effect of lime addition is the displacement of the shrinkage limit of soils. This value corresponds to the water content below which a reduction in moisture will not cause a decrease in the volume of the soil mass. If the shrinkage limit is below the placement water content, the soil can shrink due to the dry period met during a weathering cycle. The lime treatment of a clayey soil has as effect to move the shrinkage limit towards high water contents, above the optimum, reducing or even eliminating the risk of cracks.

IV.2 Lime treatment restoration projects on the Friant-Kern Canal [Howard, 1976; Herrier, 2012]

The Bureau of Reclamation began using lime treatment in failed sections in 1972-73. The works on the lining could be carried out only during 2 or 3 winter months, the only time the canal could be taken out of service. The first lining project was built in 1972-73 and 73-74, and involved both earth-lined (2700 m) and concrete-lined on treated soil (550 m) sections. 2 other contract projects, involving respectively the banks and the concrete-lined sections were built during 1975-77 and 1983-84.

Figure 2 shows the cross-section of the rehabilitated earth-lined and concrete-lined sections. Thicknesses of lime-treated soil layers were approximately 1.2 m on the banks, 60 cm in the bottom and on the parallel service roads. The earth-lined section had 2:1 side slopes, instead of a 3:2 slope in the case of concrete-lined areas.

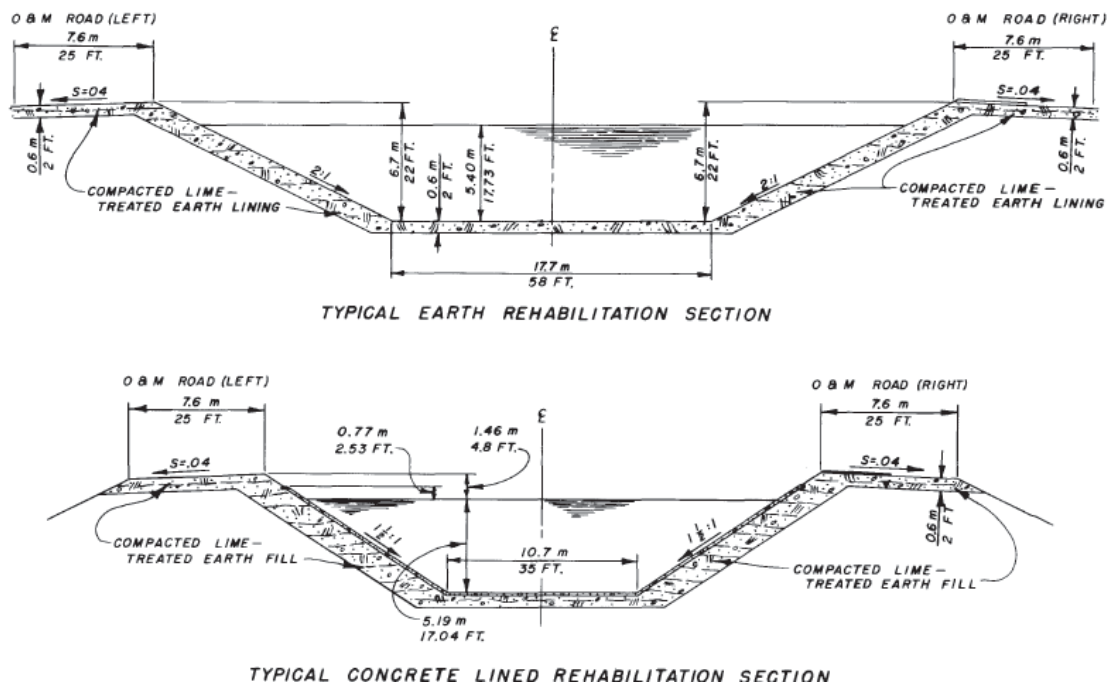


Figure 2: Cross-sections of rehabilitated canal sections (From Howard, 1976).

Determination of the lime type and dosage

The percentage of lime to add to a soil was determined according the Eades and Grim test which, following the pH evolution of a soil suspension in water, indicates the lime amount needed to reach the most beneficial effect for improvement purposes. This dosage is called the lime fixation point; if higher amounts of lime are added, stabilization through pozzolanic reactions can occur. Based on this test, 2 % quicklime could be sufficient, but a dosage of 4 % granular quicklime (90 % available lime) was recommended and

used, to compensate for variations in field construction conditions. Laboratory results indicated that this quicklime addition reduced the PI of clay from 47 to 12, and increased the shrinkage limit from 7 to 26. Increase of unconfined compressive strength was also observed to be about 20 times that of natural soil. [Howard, 1976; Gutschick, 1978; Knodel, 1987]

Construction Procedure [Gutschick, 1978]

The first stage of the program was to rebuild the service roads along the top of the canal banks to provide a stable roadway of lime-treated soil 2 m thick. For reconstructing the canal slopes, all the material which was to be treated with lime and recompacted had to be moved to the bottom. The contractor devised a “bench method” for partial treating of the bank material prior to moving it to the bottom. Half of the lime was spread and mixed in using benches to facilitate the moving operations of the initial wet and sticky soil. Once the soil placed on the canal bottom, the construction steps included scarifying and rock removal using a rock rake attached to a crawler tractor, lime spreading with a dump truck, mixing with back rippers (Figure 3, right, angle and U-dozers and graders. The presence of rocks in the soil didn't allow the use of rotary mixers, preventing a fine pulverisation of the soil and lime. However, the clay was reported as very reactive with quicklime, and after the numerous passes and mellowing, the appearance and workability of soil was considered as satisfactory.



Figure 3: Devices used for removing the failed material from the banks (left) and for soil-lime mixing (back ripper, right). (Source : National Lime Association)

After final mixing, the material was allowed to mellow overnight before placement. The soil was placed on the banks in 30 to 40 cm lifts and compacted with a vibrating sheepfoot roller (kneading compaction procedure) that was winched up and down the slope with a crawler tractor (yo-yo fashion, Figure 4).

Procedure changes and innovations during the next projects

The second project, completed between 1975-77, involved 3.7 km of only earth-lined section. All of the bank lining material was mixed on the bottom, and the treated soil was placed by scrapers in a succession of horizontal lifts (2.4 m width, 30 cm thickness) and then compacted by a sheepfoot roller, creating a treated-soil lining of 1.2 m thickness. This procedure was referred to as “stair-step” construction. The slope was trimmed with a bulldozer, followed by a fine grading. This procedure can be seen as an improvement in comparison with the “yo-yo” fashion, less risky and offering a good compaction level even at the toe of the embankment.

The third project (1983-84) involved failed sections of the concrete-lined canal. The sloughed embankment was previously removed and replacement material was obtained by mixing quicklime with clay in adjacent borrow areas and hauled to the worksite.



Figure 4: Compaction procedure on the canal banks (First project). (Source: National Lime Association)

A “yo-yo” fashion was adopted; the compaction was performed by a sheepfoot roller (kneading compaction).

V PERFORMANCE AND FEEDBACK [Gutschick, 1978 & 1985; Garver, 1987; Fleming, 1992; Herrier, 2012]

Pictures of the canal bottom were taken 1 year after the first project completion, and 1 year irrigation service (Figure 5, left). The sheepfoot roller imprints left after compaction were evident. Even 35 years after repair works, the same imprints are still visible on the blankets (Figure 5, right). Those elements indicate that the lime-treated soil was not subjected to erosion on either the bottom or the banks. According to written and oral testimonials, the lime stabilized lining has performed very well and no new slips or slides have occurred. In terms of mechanical resistance, cores taken from undisturbed block samples showed a compressive strength of 2.2 MPa (1 month after works completion) and 3.4 MPa (1 year), demonstrating additional strength evolution of the material even in constant contact with water.

Only a minor amount of erosion is visible along the water line (see Figure 5, right). This is probably due to the removal of “clay balls”, fragments of original soil that remained untreated, due to the poor efficiency of mixing operations. These minor faults don’t affect the stability or functions of the canal. It is interesting to point out that a gravel belt was originally specified at the wave line for erosion control, but lack of time permitted only a short section of gravel belt to be placed. After the first irrigation season, the USBR concluded that the erosion was not significant on the unprotected lining, and that the gravel belt was unnecessary. That decision saved \$60.000 in construction costs. In the case of the steeper (3:2) concrete-lined section, time ran out again for placing all the concrete linings on the lime-treated banks, leaving this material exposed to water flow. Even in this more confined cross-section where the flow reaches high values (above 100 m³/s, with a velocity of 1.4 m/s), no damage was identified. [Gutschick, 1978] According Mr. Tom Fusek, head of maintenance operations for a large portion of the Friant-Kern Canal, no damage has occurred on the treated sections since the restoration works; the lime stabilized lining is the material that needs the least maintenance, small amounts of loam are deposited by the water flow and are easily removed by a simple raking of the slope surface.

It should be noted that it was never an objective to seal the canal when it was being built. However, the various linings are relatively impervious. Some trees, which grew along the canal before lime treatment, since have died; the reported reason is that water no longer was leaking through the canal bank. [Gutschick, 1985]

The use of lime in the repair of slough slides has proven to be much more economical and effective than flattening the slopes with berms. It enabled the slides and bottom of the canal to be reconstructed using materials from the slides themselves, thereby reducing the right-of-way requirements and the need for additional borrow. [Fleming, 1992]



Figure 5: Pictures of the Friant-Kern Canal.

Left : sheepfoot roller imprints filled with water, at the canal bottom after 1 year irrigation (source : National Lime Association).

Right : picture taken end of 2010, during a maintenance phase. Junction of a lime-treated and an untreated zone, covered with gravels. Note the minor erosion along the wave line, and the still visible compactor imprints, after 35 years of service.

VI OTHER TESTIMONIALS, CASE OF DISPERSIVE SOILS

Beyond canal restoration projects, the applications of lime treatment for stabilization of soils were extended to levees (mainly on the Mississippi River in several states) and earth dams. In this last application, lime was used to reduce the dispersive behavior of soils, and therefore suppress erosion problems. [Gutschick, 1978, Fleming, 1992] Dispersive materials are erodible in slow-moving, or even in quiet water, by individual colloidal particles going into suspension. Lime treatment controls the soil particle dispersion, thanks to the cationic exchange and flocculation/agglomeration effects. The case of McGee Creek Dam is illustrative of lime treatment efficiency for dispersive soil improvement in hydraulic structures. [Knodel, 1987, Fleming, 1992]

The Lhoist Group, a lime producer, is currently leading a Research Project to establish the relevant properties of lime-treated soils and propose the best construction procedures to obtain homogeneous materials that, once properly compacted, can offer the best mechanical and hydraulic properties for use in levees, canals, dikes, dams... applications. This is the subject of another paper presented during the ICSE-6 Conference [Herrier]. Results of internal and external erosion test campaigns are also presented in 2 papers from IFSTTAR [Chevalier] and IRSTEA [Bonelli].

Finally, an experimental full-scale embankment was built at the Centre d'Expérimentation et de Recherche (CER) in Rouen (France), during September 2011, implementing the results of the Lhoist research project. This "dry dike" was built with a dispersive silt treated with lime, to examine the process efficiency, the behaviour of the materials and the performance of the structure vs time. Both mechanical and hydraulic measurements are being performed. This experimental structure is the subject of another paper submitted during ICSE-6 Conference. [Charles]

VII CONCLUSIONS

The use of lime treatment for hydraulic structures applications is applicable to both the highly plastic, expansive clayey soils, and the less plastic dispersive soils. An outstanding testimonial of the durability of the materials is the Friant-Kern irrigation canal in California. Since the construction period (late 1940's), the earthen banks have suffered periodic damage from cracks, slips and slides. Concrete-lined sections also show failures due to the swelling of expansive soils. In the 1970's, the Bureau of Reclamation decided to repair approximately 8.5 km of failed sections using lime treatment of clays taken from the banks of the canal. The observed performance after 35 years of service is very relevant. No new slips or slides have been observed since the rehabilitation projects in the 70's, and the lime-soil lining is the material that needs the

least maintenance on the canal. In addition to the very good mechanical and hydraulic performance of the repaired sections, including lime-treated soils under water level, this technique reduced the overall construction costs.

The use of lime for the repair of slough slides has proven to be much more economical and effective than flattening the slopes with berms, and has permitted the reconstruction slope failures in the canal by using materials from the slides themselves. In addition to reducing the right-of-way requirements and the need for additional borrow for the projects significant cost savings were achieved.

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