Landslide prediction and prevention

Prédiction et prévention des éboulements de terre

F. SILVA, Consulting Engineer, Geotechnics, Lexington, Massachusetts, USA
C. M. TROCONIS, Civil Engineer, LAGOVEN S.A., Caracas, Venezuela
T. W. LAMBE, Consulting Geotechnical Engineer, Longboat Key, Florida, USA

SYNOPSIS This paper compares the predicted performance with the measured performance of a natural slope in an oil storage reservoir at LAGOVEN's Amuay Refinery in Venezuela. During the past seven years, the authors have developed and applied a landslide prediction methodology for earth slopes at the Amuay Refinery. We applied this methodology to predict and later prevent, instability of the FORS-1 East Wall(an interior slope of an earth structure for the storage of fuel oil). The planning of remedial measures started when the computed Safety Factor for the slope dropped to about 1.1. The measures consisted entirely of drainage to control pore pressures. During the construction of self-bailing wells and a trench drain, field observations indicated an imminent landslide. The drainage successfully stopped the movement and prevented the failure of the East Wall. Three years after construction of remedial measures stability analyses indicate that the East Wall continues to meet LAGOVEN's performance criteria for stability.

PREDICTION METHODOLOGY

During the past seven years the writers have developed and applied a semi-empirical landslide prediction methodology for earth slopes at LAGOVEN's Amuay Refinery in Venezuela. We based this methodology on measured soil mechanics fundamentals (geometry strenght pore pressures) calibrated with site specific information (quantified geology, stress path to failure, landslides measurements and analyses, flow analyses, field surveillance). Figure 1 ilustrates the stability analysis method. The principal feature in the geometry consists of a layer of plastic clay with a complex geologic history. This clay layer serves as a seal wich has resulted in a perched water layer fed by water from refinery activities (pipeline leaks, hydrostatic testing of tanks, spray from cooling towers,...) The perched water changed pore pressures in the Sandy Silt and the top of the Brown Plastic Clay from negative to positive. Most landslides at Amuay involve the Brown Plastic Clay layer.
To model field conditions, we use a wedge analysis (coded in program GWA; Grismala, 1978). GWA can search for the lowest safety factor surface by varying the length and inclination of the wedge boundaries. By monitoring pore pressures and movements and with the help of index tests and flow analyses, we select the appropriate strength curve and pore pressures for the time frame in question and arrive at the predicted Safety Factor. We have found that most remedial measures take two years to implement fully without resorting to extraordinary and thus expensive, design and construction procedures. Besides minimizing surprises and increasing the safety of earth structures at Amuay, the landslide prediction methodology outlined above has impacted geotechnical construction in two ways, namely.

1. The better understanding of the landslide mechanism and engineering properties of soils permit designs with lower Safety Factors, and
2. The predictions help plan expenses avoiding unexpected expenditures during the fiscal year.

INSTABILITY OF THE FORS-1 EAST WALL + PREDICTIONS

LAGOVEN has three Fuel Oil Storage Reservoirs (FORS) at Amuay.Each reservoir consists of an earth dam connected at each end to a recess (termed "quebrada") in the natural cliffside. FORS-1 with a capacity of over 11 million barrels,has a 24 meter high by 500 meters long earth dam. A clay liner, impervious to oil, covers the reservoir bottom and inside slopes. A soil cement facing protects the clay on the slopes from erosion. The FORS-1 dam has accumulated an excellent performance record during its 29 year history. However, the reservoir East Wall has not escaped the cliffside instability problems caused by the perched water. Figure 2 shows a plan view of the East Wall and Table I chronicles the events related to the East Wall instability. We first got concerned about the stability of the East Wall in 1976 when field technicians measured high water levels in observation wells W1-5,6 and 7. However the distance between the wells and the slope and the inadequacy of the information provided by wells with long collection zones prevented us from reaching dependable conclusions. LAGOVEN proceeded with the installation of several piezometers to overcome the shortcommings of the wells. Since at the time FORS-1 stored a large quantity of oil,LAGOVEN had to install the piezometers near the crest, outside of the reservoir. Stability analysis based on measured total heads confirmed our concern for the stability of the East Wall. Figure 3 summarizes the --

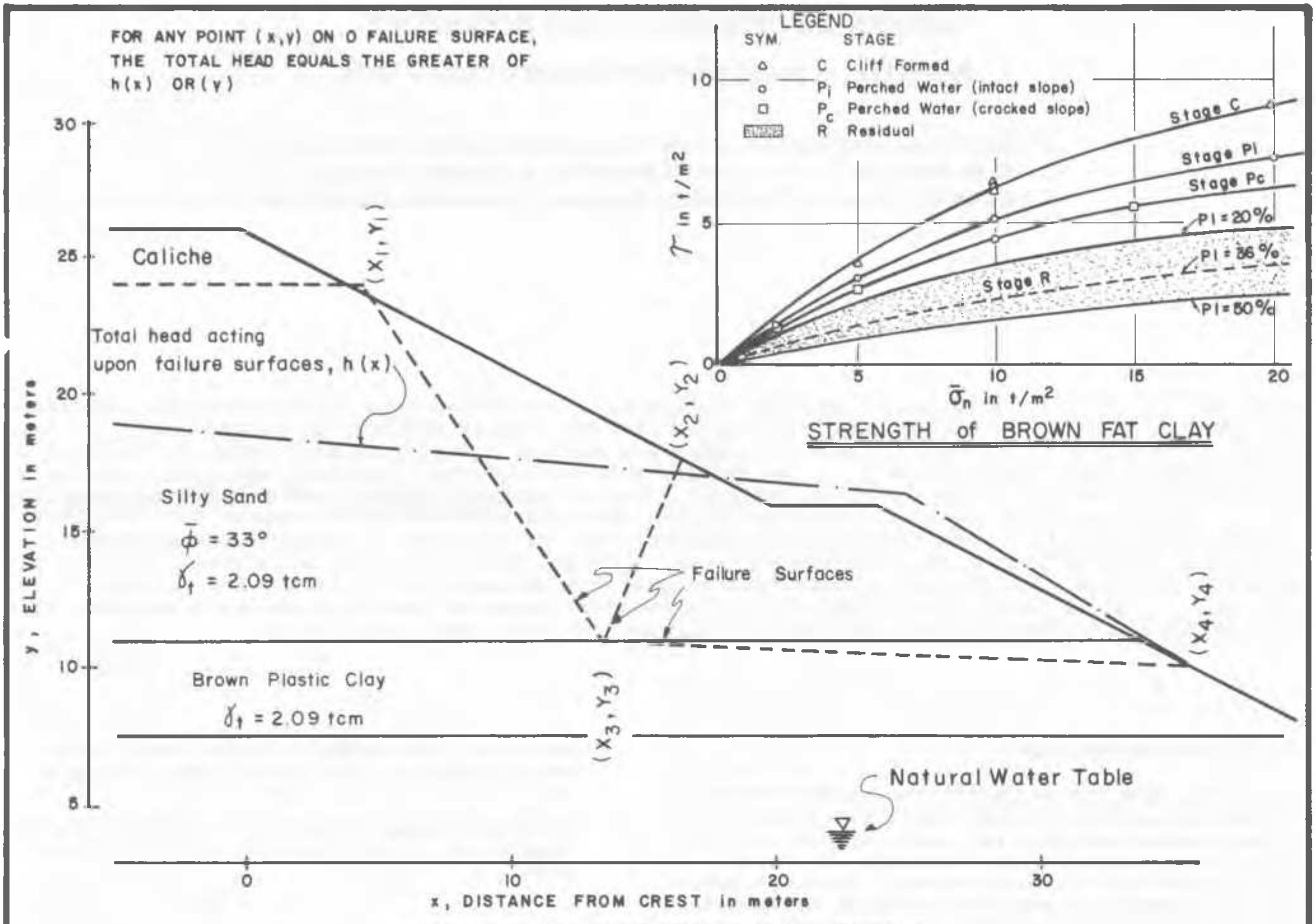

FIG. I – STABILITY ANALYSES – FORS-I

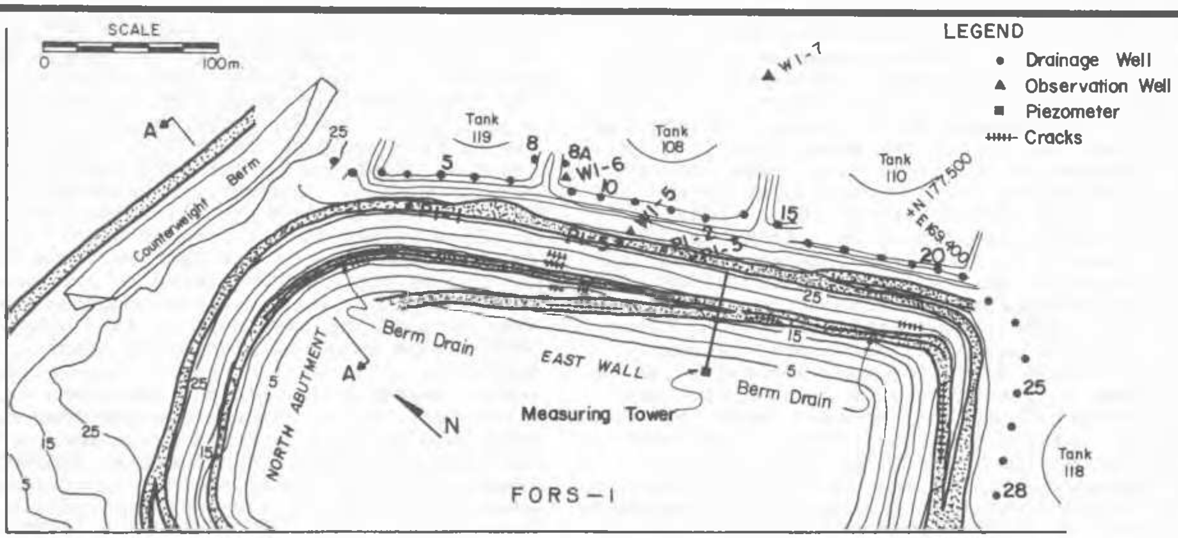

FIG. 2 – PLAN VIEW – FORS-I

stability analyses for the East Wall. On May, 1978, the Safety Factor for a "large slide" (a slide involving most of the slope) stood below 1.2. The Safety Factor for a "small slide" (a slide starting at berm level) equalled about 1.0. LAGOVEN's performance criteria required a Safety Factor of at least 1.3 with the reservoir empty for both potential slides. During -- high oil levels the weight of the oil provides a resisting force which increases the stability of the slope. We had reasonable confidence on the stability analyses for the "large slide" but did not have confidence in the results for the "small slide" due to the uncertainty in the estimated pore pressures near the toe of the slope. A 1 meter increase in total head near -- X = 34 meters results in a 2% decrease in safety factor for the "large slide" (from 1.15 to 1.13) but a 20% decrease in the Safety Factor for the "small slide" (from 1.10 to 0.9). Nevertheless, the analyses indicated a clear need for preventive / remedial measures.

INSTABILITY OF THE FORS-1 EAST WALL - REMEDIAL MEASURES

The refinery operational requirements during the late seventies ruled out taking the reservoir out of service. Therefore, we designed remedial measures for implementation in two phases. Phase I consisted of installing a line of self -- bailing drainage wells behind the East Wall and the two abutments (28 wells at 10 meter intervals, each well 35 to 40 meters deep) to intercept the flow of perched water. When refinery operations permitted, Phase II would include -- the installation of an interior drain at berm level to control total heads near the toe of potential slides. Shortly before the installation of the wells started, LAGOVEN's field technicians discovered a 27 meter long crack 25 meters south of the measuring tower at berm level. The crack (actually three sets of parallel cracks concave towards the reservoir) suggested that movement of a "small slide" had started. The well installation started at the north abutment, where maintaining the increased Safety Factor resulting from a recently installed counterweight berm depended on perched water control. After installing three wells near abutment, the drill rig moved behind the cracked area.
During the installation of the relief wells behind the cracked area, the field technicians noted development of cracks in a second zone about 80 meters north of the measuring tower. Among the several cracks, a 32 meters long crack on the ramp at elevation +11 meters sug-

Piez. No.	x	May 78	Oct. 79	Jun 80	Nov 81	Nov. 82	Nov 83
PI-5	-12.0	18.7	16.6	15.8	15.3	15.1	14.8
PI-12	0.0	18.4*	16.7	16.5	PI-12 & PI-11 AWAY FROM		
PI-11b	14.0	17.0*	15.7	16.0	DRAIN INFLUENCE AREA		
PI-17	26.0	14.2*	13.3	14.0	11.6	12.5	11.1
none	40.0	8.6	8.6	8.6	8.6	8.6	8.6

TOTAL HEADS ON FAILURE SURFACES
$h_t = y$ for points above total head line
* estimated

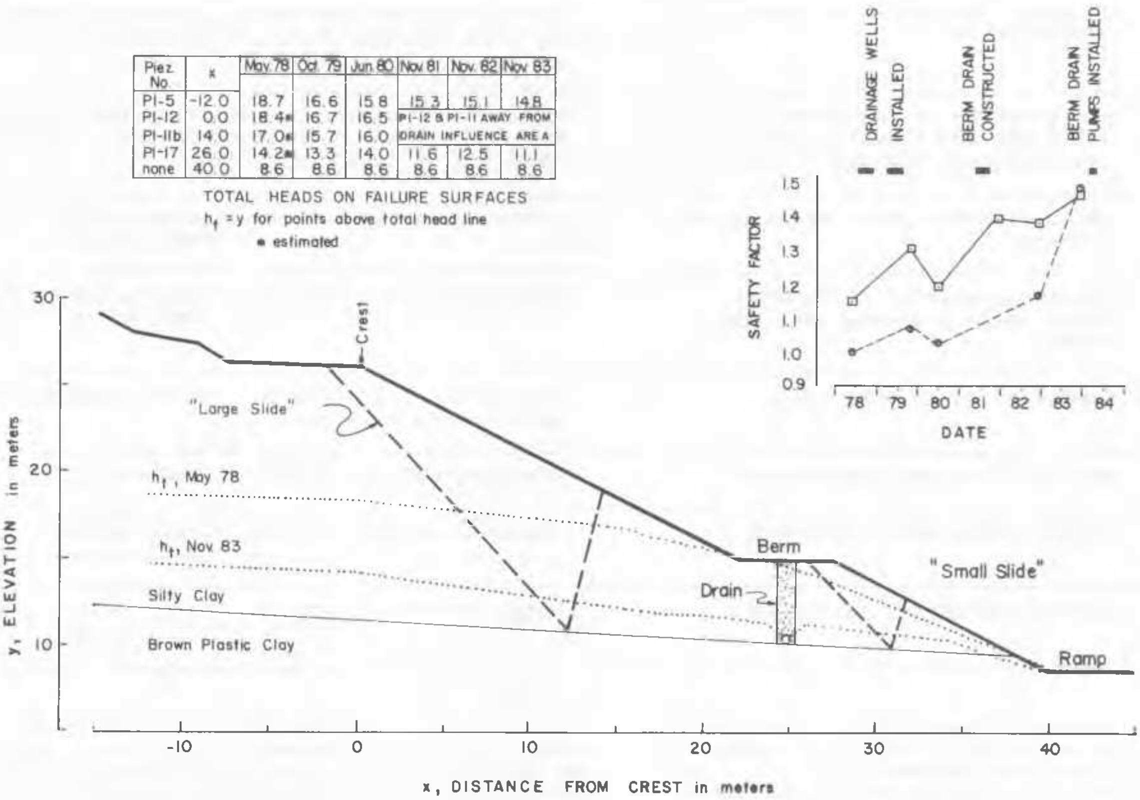

FIG. 3 – STABILITY ANALYSES
May 1978 to November 1983. East Wall – FORS-1

TABLE I

CHRONOLOGY OF EVENTS

FORS-1 EAST WALL INSTABILITY

DATE	EVENT	COMMENTS
DEC 76	High total heads in east wall raise concerns about stability of slope.	Planned installation of piezometers to evaluate the significance of these high total heads.
APR-MAY 78	Installed piezometers 1,2,3 & 5.	Computed Safety Factors: "Large slide" 1.15 "Small slide" 1.10 to 0.9 LAGOVEN's Performance Criteria required F.S.= 1.13 or higher. Refinery operations did not permit - taking reservoir out of service. Planned installation of drainage wells along the perimeter of the east wall and near the two abutments. -- Planned trench drain at berm level inside the - reservoir for installation when refinery operations permitted.
AUG 78	27 meter long crack found at bern level.	Crack suggested movement of a "small slide" had started.
AUG-NOV 78	Installation of drainage wells 1,2 3,10,11,12 & 13.	
OCT 78	32 meter long crack in ramp at elevation +11 m.	Crack suggested movement of another "small slide" had started. Moved drill rig to install wells behind crack.
NOV 78-JUN-79	Installation of remaining drainage wells and additional piezometers to help evaluate the well's performance.	Pneumatic piezometers installed inside reservoir to reduce uncertainty in total head values near toe of potencial slides.
OCT 79	Wells decrease total heads by up to 3 meters	Computed Safety Factors: "Large slide" 1.30 "Small slide" 1.08
JUN 80	Safety Assessment performed. Total heads increase near toe of slope.	Computed Safety Factors: "Large slide" 1.19 "Small slide" 1.02
MAY-AUG 81	Construction of Berm Drain	Berm drain installed in 8 meter segments to avoid slope failures.
NOV 81	Safety Assessment performed	Computed Safety Factor: "Large slide" 1.39
NOV 82	Safety Assessment performed	Computed Safety Factors: "Large slide" 1.38 "Small slide" 1.16
NOV 83	Safety Assessment performed	Computed Safety Factors: "Large slide" 1.46 "Small slide" 1.49

gested that a second "small slide" had started. After drilling wells 16,17 & 18, the drill rig moved behind this new cracked zone. The wells reduced total heads at the slope. After the installation of wells behind the cracked areas, field measurements indicated that movements stopped. Clearly, at a time when refinery operations did not permit undertaking of more radical measures from inside the reservoir, the drainage wells reversed the raising pore pressure trend at the east wall and, in the opinion of the writers, prevented the failure of the slope. Due to the presence of the clay liner, we did not expect the wells to decrease total heads near the toe of potential slides suficiently to increase the Safety Factor to the level required by the performance criterion. That task would rest upon the measures planned for Phase II. The improvements realized with the installation of the drainage wells permitted delaying the installation of the berm drain until May 1981. During this delay which avoided interrupting refinery operations, LAGOVEN engineers kept the oil level inside the reservoir as high as possible to reduce the risk of failure of a "small slide". The berm drain consisted of a 5 meter deep by 1 meter wide trench lined with filter fabric and backfilled with gravel. Prior to backfilling, the contractor placed a 4" dia. perforated pipe in the bottom of the trench. To avoid slope failures, the construction documents specified a maximum open trench length of 8 meters. The berm drain construction did not produce adittional cracking of the slope. Problems with the two sump pumps have not permitted the drain to function as designed (as of the time of this writing). LAGOVEN plans to install two specially constructed screw pumps early in 1984 to solve the bailing problems. Two relief valves on the slope surface, connected to the sumps during construction, have provided gravity drainage during the critical low oil level periods. During periods of high oil level when the valves remain submerged in oil, the weight of the oil suffices to maintain the Safety Factor above the performance criterion. Shortly after the completion of the berm drain, the East Hall slope met LAGOVEN's performance criterion for stability and the Safety Factor has remained above the criterion ever since.

CONCLUSIONS

The case study presented above ilustrates the use of a landslide prediction methodology to reduce the risk of failure of earth structures and correct deficiencies before emergencies develop. The writers have applied the prediction method in five other situations at Amuay. We attribute the success of this methodology to its foundation on soil mechanics fundamentals and the calibration of analytical techniques and parameters to the Amuay soil conditions. At Amuay the aplication of the landslide prediction method in conjunction with an ongoing Geotechnical Safety Program, has resulted in less expensive designs and greatly improved fiscal planning.

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