THE ROLE OF FIELD INSTRUMENTATION IN CORRECTION OF THE "FOUNTAIN SLIDE"

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The reliability and usefulness of field instrumentation in providing design data for landslide correction are clearly illustrated in the case history of the Fountain landslide. The area known as the Fountain Slide affects an approximately ¾-mile (1-km) section of I-80N just north of Mt. Hood about 45 miles (72 km) east of Portland, Oregon. This section of highway is flanked on one side by a railroad and the Columbia River and on the other side by the unstable and ancient landslide, which extends for several thousand feet (more than 1 km) to a sheer rock face some hundreds of feet (more than 200 m) above the lower slopes. Construction of I-80N required cutting into the unstable area a substantial distance and resulted in increased slide activity. Since the construction of the Interstate, several efforts have been made to stabilize the Fountain Slide. None have been totally successful, largely because the cause of the failure was not fully understood. In 1968 field instrumentation was installed that made it possible to carefully define the failure surface and actual groundwater conditions. This information was used to design a slide correction scheme. Construction of a $3.2-million correction scheme, which was scheduled to start in the early spring of 1973, has been delayed by further areal extension of the slide mass. The instrumentation program has been expanded to include the new unstable area. The feasibility of relocating the highway into the Columbia River or a do-nothing alternative with continued maintenance and a warning system are also being studied. The field instrumentation is being continually monitored to ensure proper design input for whatever remedy is selected.

•HIGHWAYS that are built through old landslide areas require much from the engineer. He must determine the effects of his proposed construction on an already marginal condition and show that his design will ensure adequate safety against future instabilities. This degree of precision calls for development of field instrumentation to monitor ground movements in order to define design constraints.

Many field instruments that do exactly this have been developed. Two types of instruments utilized in the analysis of a particular landslide problem are the slope inclinometer and piezometer. The slope inclinometers installed were the Slope Meter and Slope Indicator types. The piezometers were of the pneumatic type.

The area in question is located along the Columbia River in Oregon about 45 miles (72 km) east of Portland. It has been a known landslide area for many years. The first roadway was constructed over the slide in the early 1920s, and the present highway, which is part of Interstate Route 80N, the major east-west highway in Oregon, was completed in 1968. Figures 1 and 2 show the area as it existed in 1968 and in 1973. The photographs illustrate the progressive type of landslide movement that is so common throughout the Pacific Northwest.

During construction, a significant amount of material was removed to widen an existing facility to a 4-lane divided highway. This involved cutting into the unstable hillside a substantial distance. As a result, movement became a much bigger problem. This required the removal of 160,000 yd^3 (122,000 m^3) of material to reduce the driving forces and attempt to stabilize the slide activity that was taking place.

In 1968 the first set of slope inclinometers was installed to define the failure surface and groundwater conditions. During the initial field instrumentation installations, two types of slope inclinometers were used—the Slope Indicator and the Slope Meter. The only available Slope Indicator casing at this time was approximately 3.5 in. (9 cm) outside diameter, and this required the drilling of two holes at each Slope Indicator location. The reason was that the subsurface exploration required the use of a core drill that is of a smaller diameter than the 3.5 in. (9 cm) required for the Slope Indicator. The Slope Meter requires a 1¾-in. (4.4-cm) square steel casing, and this eliminated the need for additional larger diameter holes. "H" series wire line drill tools were used, through which the square steel casing could be placed after completion of the core drill hole. A substantial drilling cost savings was realized during this initial work by switching to the Slope Meter. The later development of the smaller Digit-Tilt by Slope Indicator would have eliminated the need for the extra drilling.

Unfortunately, slide activity since completion of the project has required extensive maintenance work on the highway and railroad grade. During periods of movement, shifts in the railroad grade or alignment were corrected on a day-to-day frequency. Figure 3 shows the many inclinometers that have been installed because of the magnitude of movements and the scarp as it exists now along with the landslide limits of 1968. The present total area of sliding extends along the highway approximately ¾ mile (1 km).

SUBSURFACE CONDITIONS

Subsurface investigation work began in June 1968, and inclinometer casing was installed at each of the test boring locations so that water levels could be measured and slide movement monitored using Slope Meter and Slope Indicator equipment. Transit traverses were also run along the existing highway and railroad to measure surface movements. The slide mass is primarily a talus-like material ranging from a vesicular coarse-grained andesite to a fine-grained basalt. Matrix material varies from silts and sandy silts to sandy silty clay. Lenses or zones of siltstones, claystones, sandy-pebbly-rocky siltstones and sandy-pebbly-rocky claystones occur throughout the sliding mass. As shown in Figure 4, the degraded claystones and siltstones have been grouped together under the term "clay" or "mudstone". Weathering of this "mudstone" resulted in a weak zone within the subsurface profile. The instrumentation indicates that the slide movement is occurring within or along the surface of the clay-mudstone layer. Shear zones were evident on all the core samples obtained from the clay-mudstone layers.

The slide is moving along generally uniform slip planes with inclinations ranging from 4 to 16 deg from the horizontal. As Figure 4 shows, the slope inclinometers indicate a classic example of planar movement. The depth of movement varies throughout the landslide area, with the deepest movements 200 ft (61 m) at boring hole number SM-7. Lateral movement was quite restricted vertically in many of the inclinometer casings. Most of the bending took place on a 2 to 4-ft (0.6 to 1.2-m) interval that corresponded to the thickness of the clay-mudstone layer. The movement was generally in a northerly direction toward the Columbia River.

INSTRUMENTATION DATA

To date a total of 63 slope inclinometer casings have been installed. Many graphs have been prepared from Slope Indicator and Slope Meter data relating lateral movement to time and rainfall. Because of the excessive amounts of these movements, most of the slope inclinometer casing installed during the initial exploration has been sheared off. Prior to 1970, measured movement was at a rate of 2 ft (0.6 m) per year horizontally and 1.5 ft (0.5 m) vertically. Resurfacing of the existing pavement required a horizontal line shift of up to 5 ft (1.5 m) in some areas. This resulted in removal of some of the existing rock buttress and explains the increased rate of movement that occurred shortly thereafter. As can be seen from Figure 6, the rate of movement differed considerably throughout the area of sliding.

Figure 5 is representative of the lateral movements that have taken place from 1968

Figure 1. 1968 aerial photo showing existing landslide limits.

Figure 2. 1973 aerial photo showing existing landslide limits.

Figure 3. Plan of Fountain Slide showing instrumentation locations and limits of landslide. Contour intervals are 50 ft (15.24 m). SM = Slope Meter or Slope Indicator; OW = observation well; VD = vertical drain; DH = drill hole.

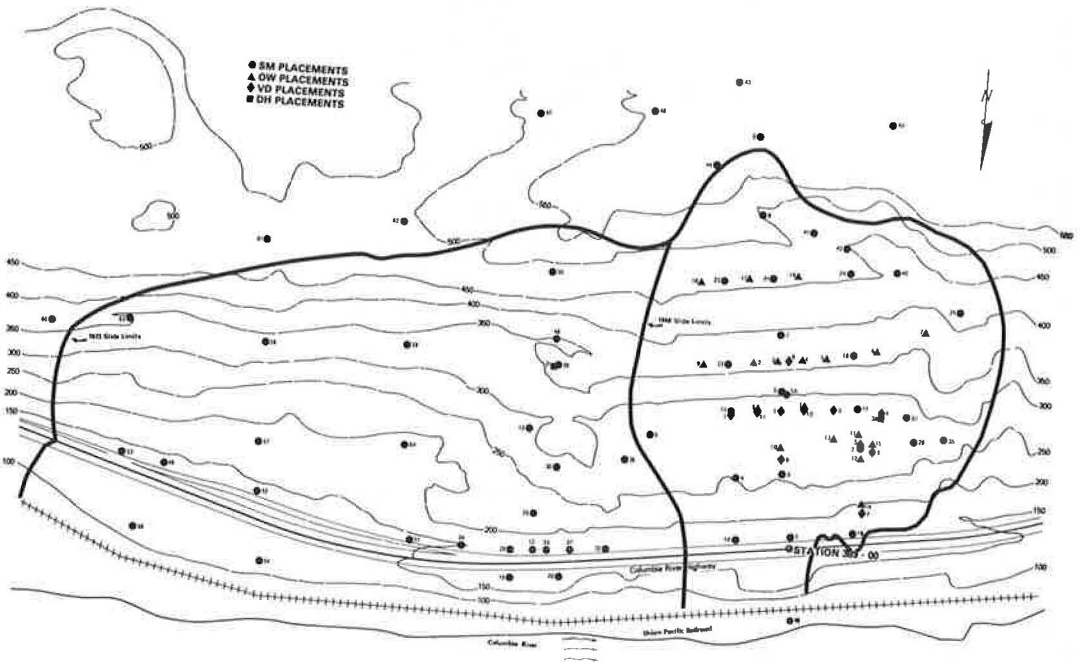
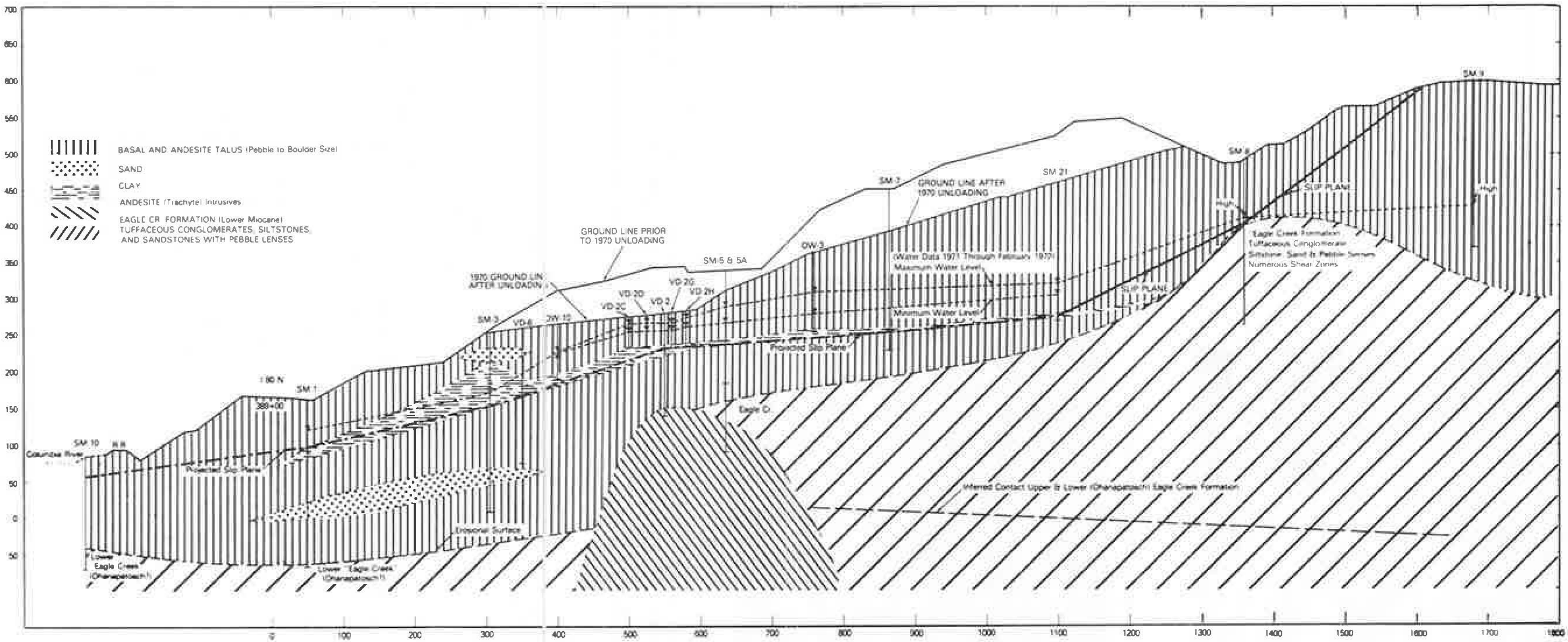


Figure 4. Cross section of Fountain Slide showing soil profile and slip plane as defined by slope inclinometers. Horizontal and vertical scales are in feet (1 ft = 0.3 m). SM = Slope Meter or Slope Indicator; OW = observation well; VD =vertical drain.



to 1972. Several slope inclinometer plots have been superimposed on the same graph to show the different types of plots from different areas of the slide. An observation that can be made from the plot is that when the movement was within a 0.5-in. (1.3-cm) range, the movement was pretty well confined to the soft zone, but once the magnitude of movement went beyond that range, the mass above the sliding plane would show uniform movement equal to the movement at the soft zone.

Measurements of horizontal and vertical displacement along the existing highway and railroad were also made and correlated with the field instrumentation data. During a 1-year period (1968-69), a horizontal displacement of approximately 2 ft (0.6 m) along the highway and 1.5 ft (0.5 m) along the railroad occurred. Vertical displacement along the highway and railroad for the same period of time varied from 0.68 to 1.56 ft (0.21 to 0.48 m) respectively. Figure 6 shows the horizontal movement that occurred on a section of the Interstate from February 5, 1968, to January 20, 1969. As would be expected, the areas showing the greater horizontal movement were the areas where the slip plane inclination was greater. It was generally established that slip plane inclinations greater than 12 deg from the horizontal showed a definite higher movement rate. These are the areas where the railroad grade and alignment must be corrected on a day-to-day basis during the rainy season when the rate of movement is high.

Figure 7 correlates the rainfall and the corresponding movement in the slope inclinometers. The graph was put together by assembling and correlating monthly slope inclinometer readings for several instruments for the period between 1970 and 1972; therefore, the plots are not actual for any one year. They indicate what has always been obvious and what many engineers have stated in the literature: The increase in sliding movements is a direct function of increased rainfall activity. Groundwater conditions throughout the slide mass do not conform to any uniform pattern; therefore, groundwater conditions varied throughout the landslide area for stability analyses. Seasonal fluctuations at the boring locations have been very erratic, which gave an indication of the variable permeability throughout. There are many zones of trapped or perched water tables through the sliding mass.

REMEDIAL DESIGN

Since completion of the Interstate Highway in 1968, several attempts have been made to stabilize the sliding mass. In December 1969, a contract was awarded for the removal of 1,700,000 yd^3 (1,300,000 m^3) of the sliding soil matrix, plus provision for drainage by installation of horizontal drains (Fig. 2). This work was completed in the fall of 1970 at a cost of approximately \$1.7 million. Eleven slope indicators were installed to monitor and assist in evaluating the stabilizing effect of the unloading work.

Instrumentation data showed that a movement pattern then developed in which ground movements occurred in the fall and winter during the rainy season and stopped during the dry summer months (Fig. 5). Movement had occurred both summer and winter prior to the 1970 unloading, which indicated that the unloading work had some stabilizing effect. Field instrumentation detected continued ground movements, and a decision was made to further attempt to drain the slide. The horizontal drains that were installed earlier gave very poor results; therefore, vertical test wells were proposed before proceeding with a well system to drain the slide. Four vertical test wells were installed during June 1971. Eight piezometers were installed around each of the vertical test wells to monitor groundwater fluctuations. Boring data had indicated that permeable talus material existed below the impermeable soft clay material (Fig. 2). The idea was to provide an escape for the trapped water through the impermeable clay into the permeable talus material below the slip plane.

An 8-in. (20-cm) unperforated casing was installed to the soft clay unit. A perforated 6-in. (15-cm) casing was then installed through and below the impermeable clay unit. Pump and bail tests were run on all the wells, and the results were as follows: well 1, bail test, 1 gpm (0.004 m^3/min); well 2, pump test, 45 gpm (0.17 m^3/min); well 3, bail test, 1 gpm (0.004 m^3/min); and well 4, bail test, 1 gpm (0.004 m^3/min).

Based on these test results, it was concluded that the material in the areas of wells 1, 3, and 4 was too impermeable for the wells to function effectively. The piezometers

Figure 5. Typical slope inclinometer plots (1 in. = 2.54 cm).

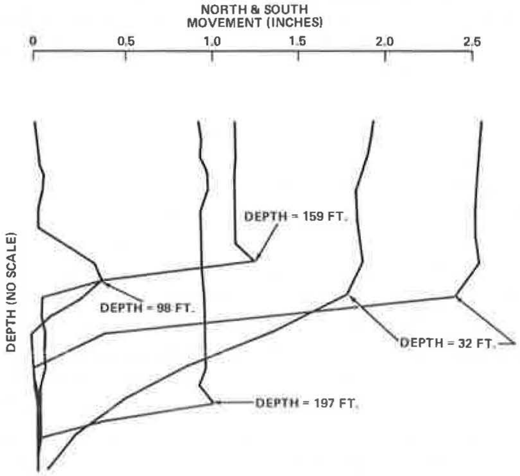


Figure 6. Highway horizontal movement.

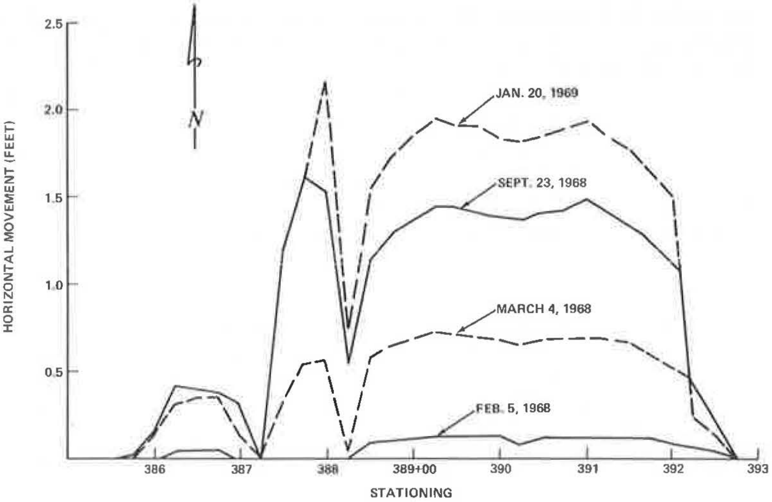
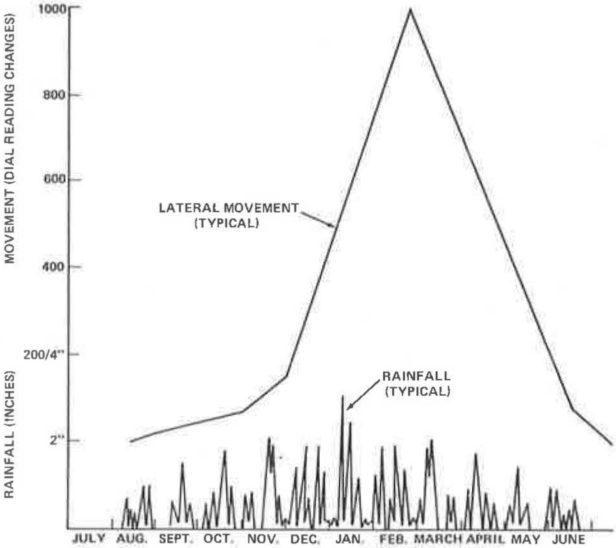


Figure 7. Rainfall versus movement.



in the area of well 2 indicated that the water level was lowered some 8 ft (2.5 m). Based on this one good result, it was decided to install 7 additional wells before a decision to abandon this method of drainage could be made. This drainage work was completed in October 1971 and included a total of 11 vertical wells, 48 piezometers, and 11 more slope inclinometers. Except for a few wells, the drainage worked poorly because of the very low permeability of the slide debris. Therefore, the number of wells that would be required to dry up the slide would be many more than was originally anticipated. Other disadvantages to the well system were that the annual maintenance on the pump system would be high and further movement could destroy the wells. This alternative was therefore abandoned.

During the period from November 1971 to February 1972, the slope inclinometer movement ranged from 2 to 7 in. (5 to 18 cm), depending on the location of the tube. This movement clearly defined the slip plane, as shown in Figure 4. With the location and angle of the slip plane now clearly defined, a stability study was undertaken and an elaborate remedial scheme proposed. This scheme proposed to (a) reduce the driving forces at the head of the slide by unloading where the inclination of the failure surface was greater than the angle of internal friction and (b) construct drainage trenches perpendicular to the highway centerline. The purpose of the trenches would be to improve drainage and accommodate construction of a rock buttress. The cost for this remedial scheme was estimated at $3.2 million, and construction was scheduled to begin in June 1973. During March 1973, surface observations indicated slide activity approximately 2,000 ft (600 m) east of the slide limits that were used for the remedial cost estimate. This newly observed areal extension of the landslide limits approximately doubled the sliding mass. Fifteen slope inclinometers were installed during April to June 1973 in the new area of sliding to monitor the movements and determine the slip plane. Because of the size of this sliding mass, a decision was made to wait on the proposed remedial work until the new area of sliding could be fully evaluated.

Three alternatives are under study by the Oregon State Highway Division. The alternatives are as follows:

1. Follow the remedial scheme as described above at a cost of $3.2 million and plan for remedial work on the new area of sliding once the field instrumentation data have been evaluated.
2. Consider the feasibility of moving the highway and the railroad location north into the Columbia River. The cost of this alternative is quite high (approximately $10 million) and, with the new environmental policies, this alternative seems unfeasible. The state is also checking into the possibility of relocating to the south; the estimated cost is also high and the route would be through other potential slide areas.
3. Consider the feasibility of maintaining the present location with no remedial work. An instrumentation system is under study whereby a warning signal would be given at a predetermined movement rate to warn the motorist of any impending danger. Maintenance cost figures are under study for a cost comparison with the other alternatives. If further study and monitoring of the instrumentation determine that the slide is in an advanced stage of development and some prediction may be made on when it will develop into a condition of equilibrium, this alternative may turn out to be the direction to follow.

CONCLUSION

In this paper, we have presented a case history that demonstrates the use of field instrumentation to study the progressive movements of the Fountain landslide. Data from the field instrumentation were used to define the failure surface and give a better understanding of the cause of the failure. The situation is now a matter of evaluating the three possible alternatives and making a decision on the remedial scheme. A total of 63 slope inclinometer casings have been installed.

The following observations have been made: In landslide areas such as this, where the major cause for movement is "trapped water" caused by underground streams and fractures in the bedrock, the remedial design is extremely difficult. With the present state of the art on subsurface exploration, the only means of locating this trapped water is by vertical borings. In areas as massive as the Fountain Slide, this becomes a nearly impossible task. Some drainage was very effectively placed as a result of being carefully located by borings, but many more areas of trapped water still exist, as is evident by the continued movement. If all the drainage paths providing water to the sliding mass could be located and adequately drained, the slide would undoubtedly be stabilized.

Landslide corrections are difficult to design and costly to correct; however, without proper means of identifying the depth and extent of such movements as well as the various soil, rock, and water parameters, a remedial method having any degree of reliability would be improbable.

One must always remember that instrumentation used in soil and rock mechanics is best utilized if it is simply constructed and easily observed. Very sophisticated approaches to instrumentation often lead to breakdowns during installation or difficulty in calibration during operation. It is indeed a challenge to seek better, but simpler, approaches to field instrumentation methods.