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Numerical assessment of an estimated slip surface, Locke Island landslides, Columbia River, South-central Washington State, USA

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ABSTRACT

Results of slope stability analyses for an inferred slip surface in a landslide along the Columbia River in the State of Washington are presented. The numerical analyses were made using limit-equilibrium-based computer program SSTAB2 and a commercially available continuum-mechanics-based computer program, FLAC. For the known and best understood/estimated field conditions, results of SSTAB2 analyses indicate validity of the inferred slip surface. However, the same is not true with the results of FLAC. Reasons for the differences in results from the two essentially independent methods of analysis are discussed. Preference for use of one method over the other in studying occurrence of ground instability is indicated. Usefulness of the two methods of analysis in quantitative assessments of landslides is mentioned.

INTRODUCTION

One of the most important tasks in investigation of a landslide is determining the location and geometry of the slip surface along which movement has occurred. Various means to obtain this information include: surface mapping; subsurface investigations using geophysics, drill holes, and trenches; inclinometer data; careful removal of landslide material to expose the slip surface; and making back-calculations using slope-stability analysis procedures. These means have been used in the past with varying results.

Figure 1 shows a large group of irrigation-induced landslides in the 50-km-long White Bluffs area along the east side of the Columbia River in south-central Washington State. The Locke Island landslides area is situated on the east bank of the Columbia River at the northern end of the White Bluffs. In the early 1980s, the Locke Island landslides were the most active in the White Bluffs; individual landslides in the group had moved out into the northeast channel of the Columbia River as far as 150 m. The Locke Island landslides are a series of individual landslides with merged boundaries; collectively, these individual slides have also been referred to as the Locke Island landslide — a singular (Bennett, 2002; Chugh and Schuster, 2003) rather than landslides — a plural (Schuster et al., 1989). This discrepancy in nomenclature has been corrected in this presentation with a preferred use of the word landslides. The total area of landslides is estimated to be about 68 ha with 59 ha being active during the past 25 years; total volume of these active landslides is estimated at about 12 million cubic meters (Schuster et al., 1989). Figure 2 presents a 1985 view of the Locke Island landslides.

The Locke Island landslides have been studied by a number of experts from the U.S. Geological Survey, U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, and others working in the private sector on behalf of the U.S. Department of Energy because of the location of the landslides near the Hanford Site with nuclear facilities. Locke Island is located opposite the landslides near the middle of the Columbia River and has historical and cultural significance to Native American nations in the area. In part, these studies have contributed to our understanding of the potential cause(s) of the ground instability at this site, and have provided drill-log data and interpretation of the site geology, regional and local groundwater conditions, river-surface levels, field surveys (including geophysical seismic refraction and time-domain electromagnetics), and laboratory tests on selected soil samples collected from different geologic units at various elevations.

Figure 3 shows the Locke Island landslides area. Figure 4 presents cross section F-F' through one of the largest landslides (as of 1980) in the Locke Island area. These figures are taken from Schuster et al. (1989), in which the authors suggested that the landslide movement was most likely a combination of rotation and translation, and they included the inferred failure surface shown in Fig. 4. They arrived at the location of this failure surface not by slope-stability analysis, but by a material-balancing procedure.

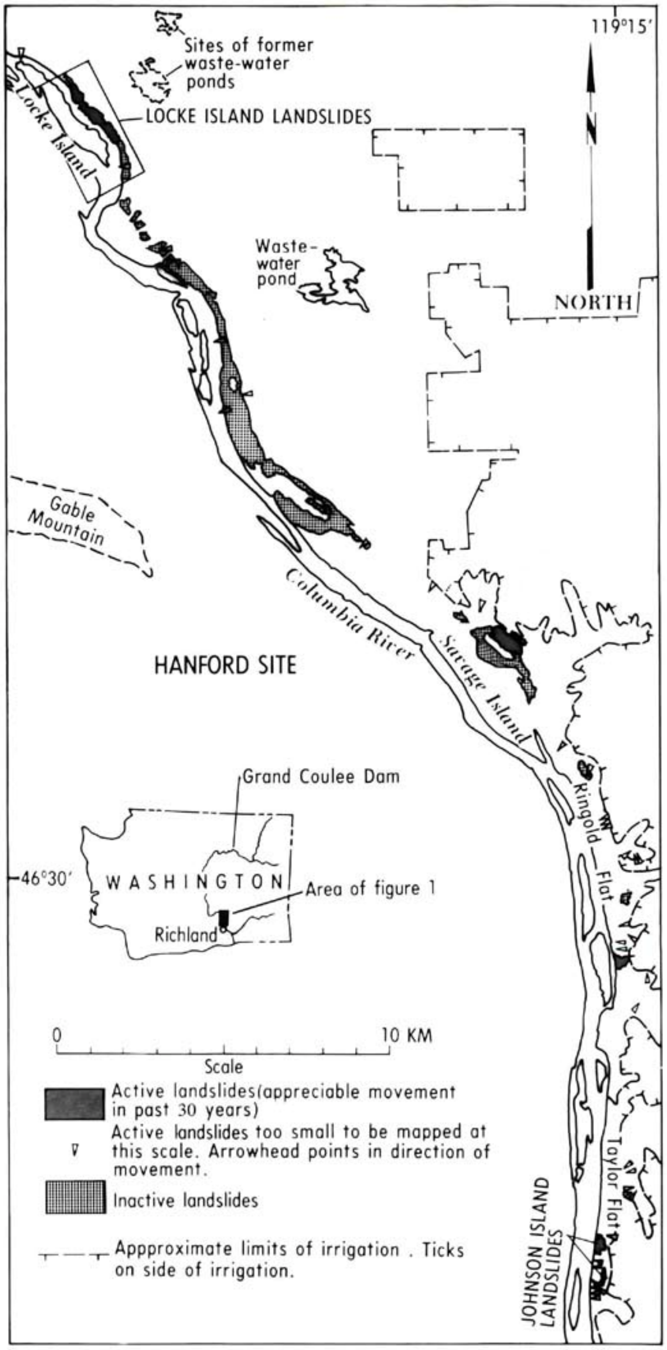


Fig. 1. Map of irrigation-induced landslides area, south-central Washington (Schuster et al., 1989).

The objective of this technical note is to present the results of slope-stability analyses for the inferred failure surface shown in Fig. 4 using likely ground-water conditions for the 1980 landslide and estimated material properties. This technical note has a narrow focus, and the lesson learned is considered to be of use in numerical analysis of slope failures. The information presented is derived from a recently completed report on numerical analysis of the Locke Island landslide (Chugh, 2002); copies of this report can be obtained from the senior author on request. Also, results of numerical assessments and their comparisons with field observations in terms of stability/instability, extent of movements, and field instrumentation data for the approximately 3.5-km length of the bluff along the river are presented in Chugh and Schuster (2003). These details are not included in this note to avoid duplication and to conserve space.

Fig. 2. Locke Island landslides, 1985 view, looking northwest (Locke Island is at far left).

SITE GEOLOGY

In broad terms, the site geology has been described as 50 to 70 m of the lacustrine Ringold Formation with three subunits, consisting primarily of silt and lean clay (Trl_a), fat clay (Trl_b), and primarily fine-to-medium sand with silt and some clay (Trl_c) deposited in a low-energy environment, overlain by 20 to 40 m

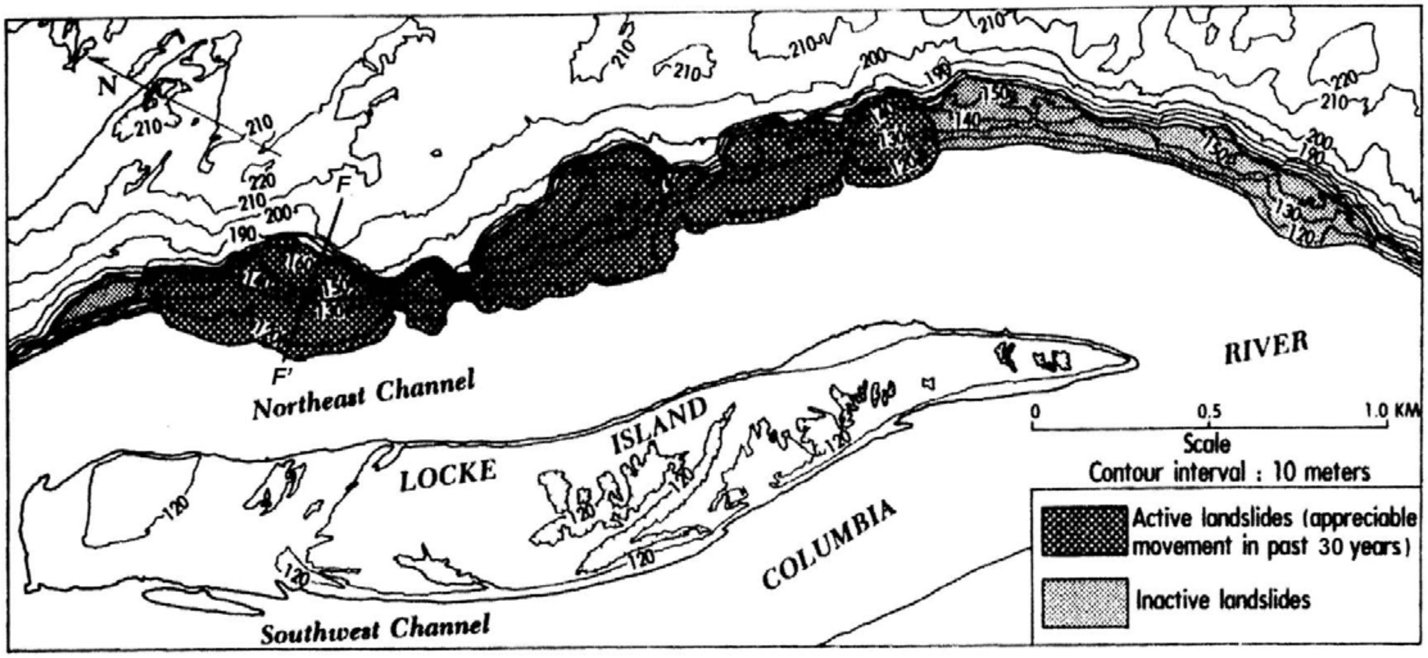


Fig. 3. Locke Island landslides area (Schuster et al., 1989).

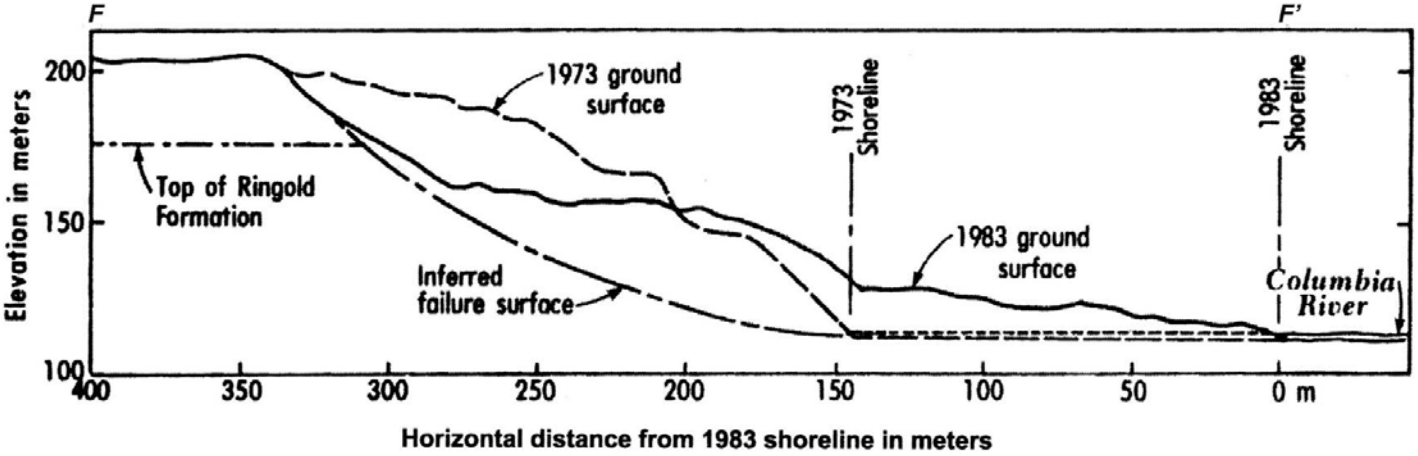
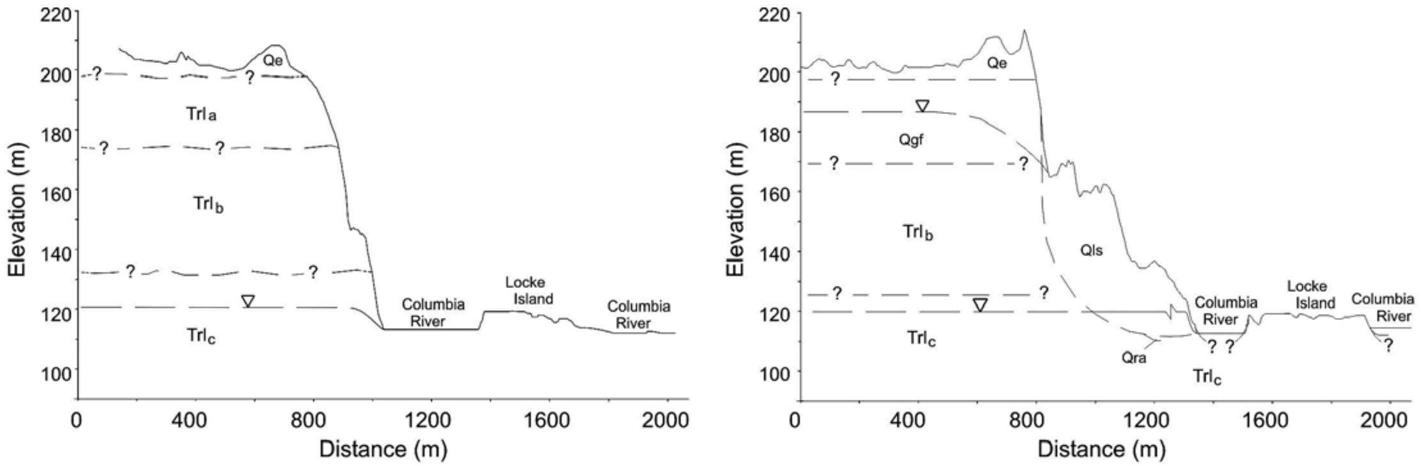


Fig. 4. Cross section F-F' (Fig 3.) through one of the largest landslides in the Locke Island area (Schuster et al., 1989).

of Quaternary fluvial and windblown sediments (Qgf) consisting of silt and sand with some lean clay intervals. Rocks of the Columbia River Basalt Group underlie the Ringold and are not exposed in the area. Figure 5 shows the spatial layout of the geologic units at the six cross-sectional locations shown in Fig. 6 along an approximately 3.5-km landslide-affected length of the bluff along the river. Ground-water conditions at these locations are also included in the cross sections shown in Fig. 5 (Bennett, 2002).

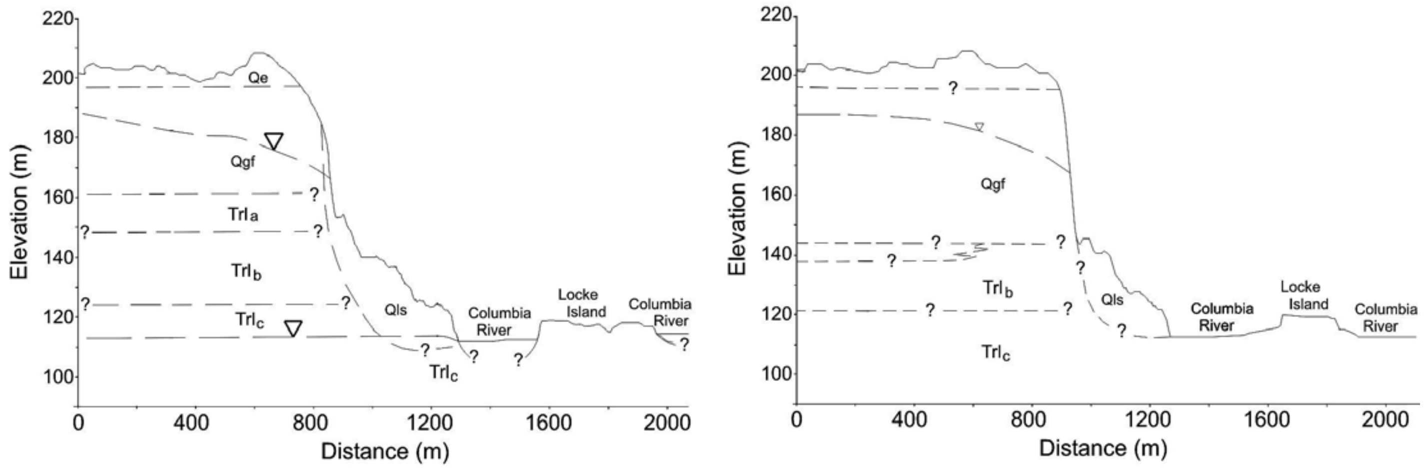
CAUSE(S) OF THE LOCKE ISLAND LANDSLIDES

For prehistoric landslide activity at the site, river erosion of the toe of the slope has been listed as the likely major cause, with landslide debris having been partly carried away by the river. For the landslide activity of the early 1980s, the cause has been attributed to the wetting of the geologic materials by water that seeped to the bluffs from irrigation wastewater ponds that were



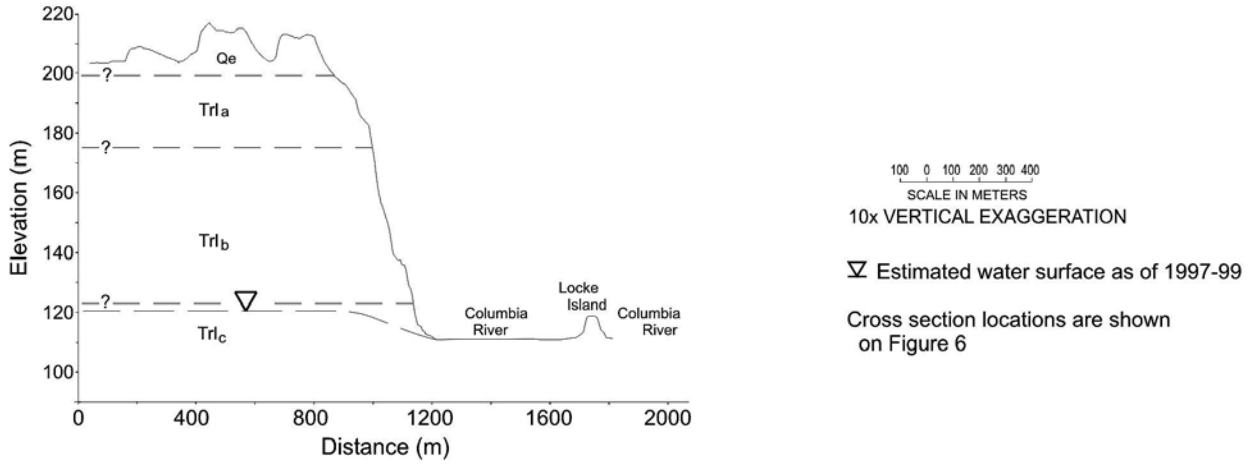
Cross section A-A'

Cross section B-B'



Cross section C-C'

Cross section D-D'



Cross section locations are shown on Figure 6

Cross section E-E'

Fig. 5. Geologic cross sections, Locke Island landslides (Bennett, 2002).

created in the 1970s in the large-sized local depressions in the relatively flat areas behind the high bluffs. These ponds provided a habitat for waterfowl and associated wildlife. After the landslides of the early 1980s, seepage emerged from the bluffs as springs flowing from the landslide head scarps. Figure 7 shows irrigation wastewater seepage from the face of a head scarp of an active landslide in the Locke Island slides area.

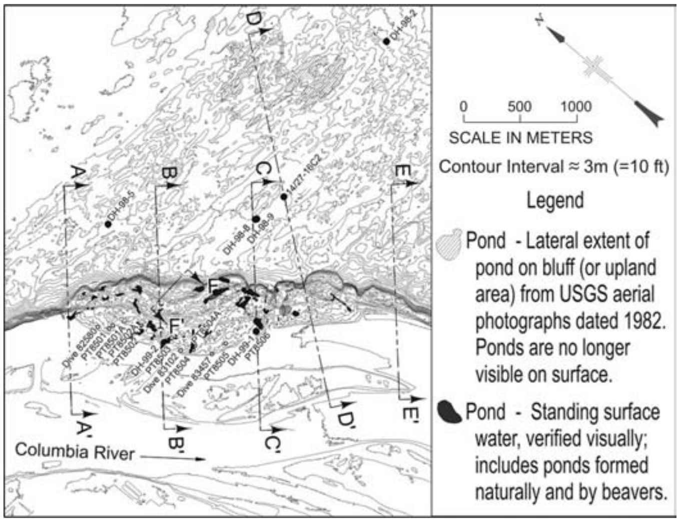


Fig. 6. *Location map of Locke Island landslides area for numerical assessment study (Bennett, 2002).*

Fig. 7. *Seepage of irrigation wastewater from face of 40-m-high head scarp of an active landslide, Locke Island landslides area (Schuster et al., 1989).*

GROUNDWATER CONDITIONS

The regional groundwater table in the Locke Island area is known to be at elevation 122 m. Groundwater flows toward the Columbia River, which was assumed to be at an elevation of 116 m (Columbia River water-surface elevation near Locke Island fluctuates as much as 6 m in 24 hours because of water releases at upstream dams). The windblown and the glaciofluvial sediments are highly permeable. The Ringold formation units are relatively less permeable. For analysis of the 1980 slide, the Qgf, and Trl_a and Trl_b subunits were considered to be fully saturated with separate phreatic surfaces (i.e., perched water tables). The phreatic surface at the top of the Qgf defined pore-water pressure in the Qgf unit and the other, at the top of the Trl_a subunit, defined pore-water pressure in the Trl_a and Trl_b subunits. Water exited along the exposed sloping faces and flowed into the Columbia River. The regional groundwater table was considered to define pore-water pressure in the Trl_c subunit.

Table 1. Material properties for slope stability assessment, Locke Island landslides.

Material unit	*Density*	*Material strength*		*Elastic constants*	
	ρ (kg/m^3)	c (kPa)	φ (°)	Bulk modulus (kPa)	Shear modulus (kPa)
Eolian sand (Qe)	1440	0	30	5.75e3	4.17e3
Glaciofluvial sediments (Qgf)	1760	0	30	2.15e5	1.63e5
Ringold Formation: Brown lean clay (Trl_a)	2240	191.5	0	1.58e7	1.10e7
Ringold Formation: Blue/gray fat clay (Trl_b)	1600	191.5	0	1.58e7	1.10e7
Ringold Formation: Differentially cemented sands (Trl_c)	1840	0	32	1.58e7	1.10e7
Landslide debris (Qls)	1840	34.4	20	7.18e5	4.79e5
River alluvium (Qra)	2000	0	35	6.22e6	4.31e6

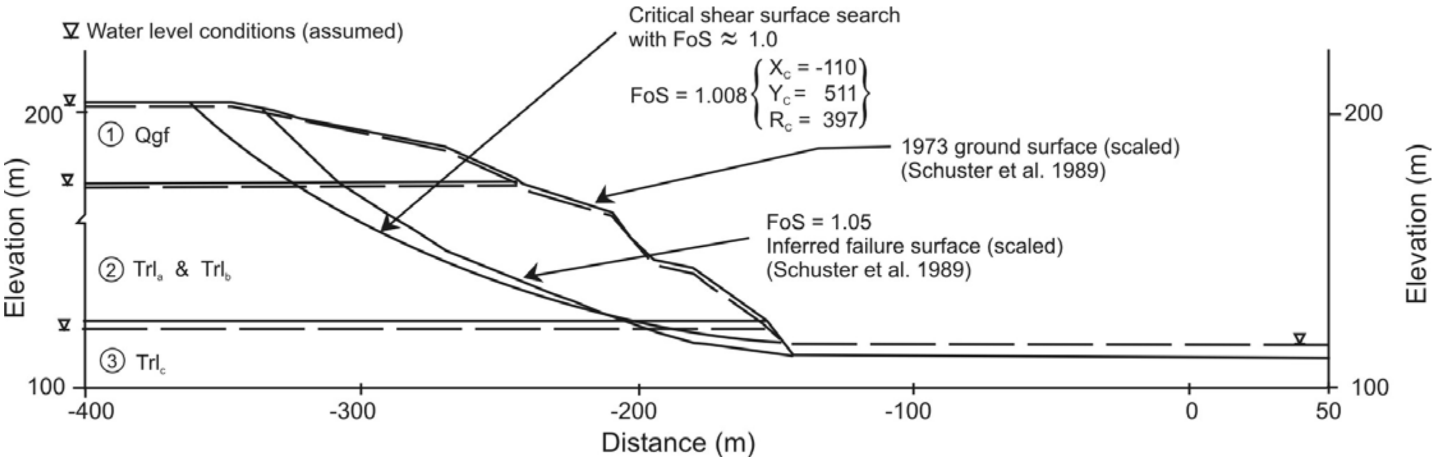


Fig. 8. SSTAB2 model for the cross section F-F', Fig. 4.

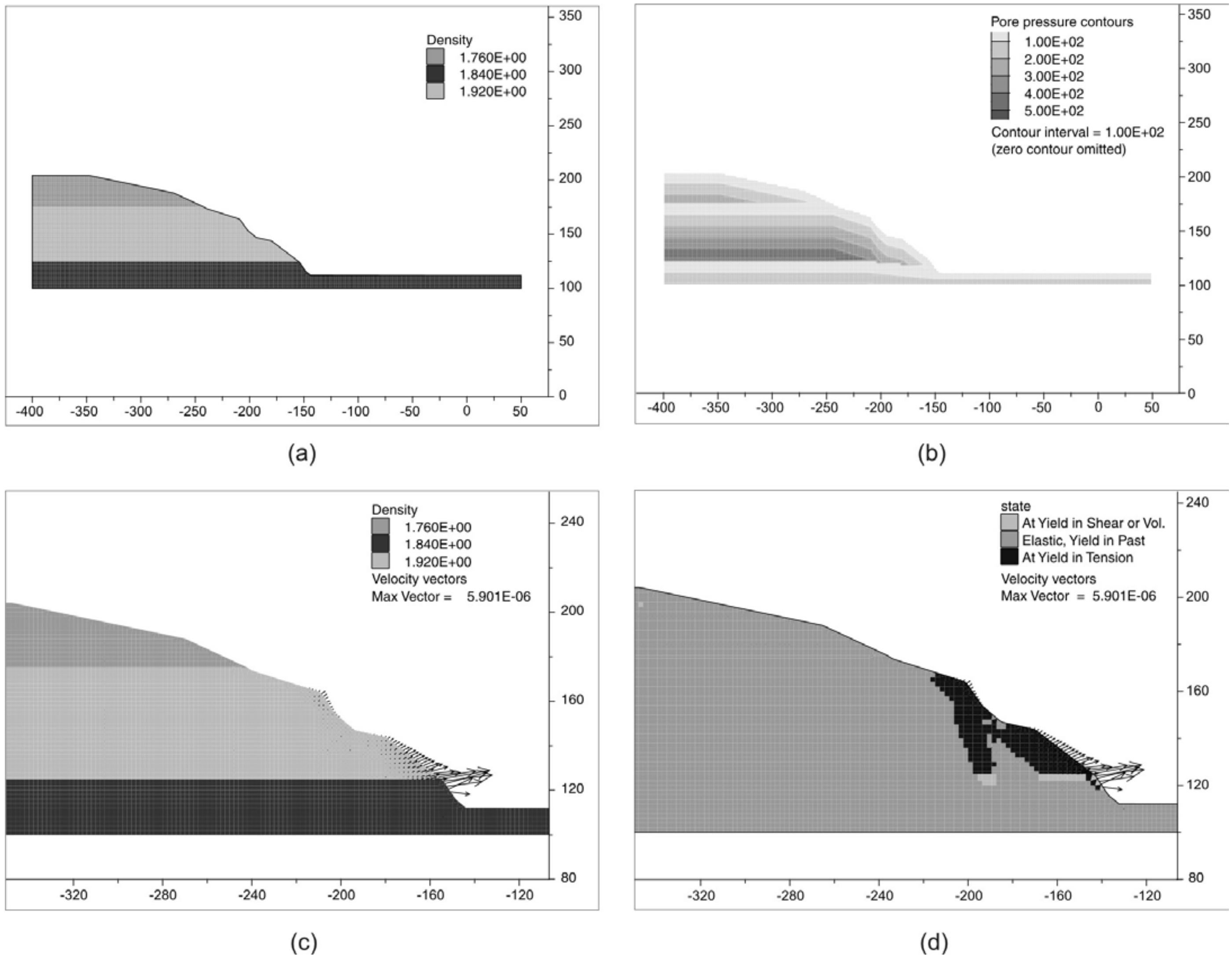


Fig. 9. FLAC model for the cross section F-F', Fig. 4.

MATERIAL PROPERTIES

Table 1 summarizes material properties selected for the various geologic units shown in Fig. 5, based on site-specific field and laboratory data (Schuster, 1981; Markiewicz, 2001) and published information where site-specific information was not available. Selections of material properties and ground-water conditions were made prior to making numerical analyses.

ANALYSIS PROCEDURES

Two different analysis procedures were used in performing the numerical calculations: computer program SSTAB2 (Chugh, 1992) and FLAC (Itasca, 2000). SSTAB2 is a limit-equilibrium-based slope-stability analysis procedure and FLAC is a continuum-mechanics-based stress and deformation-analysis procedure. Theories and ideas implemented in these programs have been used with success in the past in analyzing geotechnical engineering problems.

ANALYSIS RESULTS

Figure 8 shows the problem setup and results of slope-stability analyses using computer program SSTAB2. For the 1973 ground surface and the assumed groundwater conditions and material-properties data, the factor-of-safety (FoS) for the inferred failure surface shown on Section F-F', Fig. 4, is 1.05. From the critical search procedure used in SSTAB2, the shear surface with the computed value for FoS ≈1.0 is also shown in Fig. 8.

Figure 9 shows the problem setup and results of FoS calculations using the computer program FLAC. The FLAC results are a natural outcome of the stress analysis and the FoS value is determined using a strength-reduction methodology to bring the soil mass to the verge of failure resulting in numerical instability. Thus, the procedure finds the lowest FoS and the associated failure surface. For Section F-F', the FLAC FoS calculations indicate a local instability in the form of a small failure near the toe of the slope as implied by the velocity vectors shown in Fig. 9(c) and spread of plastic yielding and tensile failure shown in Fig. 9(d). At the Locke Island site, such small slips/sloughs most likely preceded the large slope failure which is the item of primary interest in this technical note.

COMMENTS

It is remarkable that for the existing geologic, groundwater, and material parameters, the slope stability analyses of Section F-F' and of the inferred failure surface in Schuster et al. (1989) both provide a FoS ≈ 1. This is significant because it illustrates the insight of the U.S. Geological Survey personnel in estimating the location of the slip surface at one of the largest landslides at the Locke Island site. Finding shear surfaces with FoS of lower values is not relevant because local failures most likely did precede or accompanied the larger landslide movement.

In SSTAB2 and many other limit-equilibrium-based analysis procedures, results of critical search are sensitive to the starting estimate for the location of the shear surface and the accuracy limits specified for the search. With this flexibility in the computer search procedure, several searches for critical surfaces can be performed. Acceptability of the results of critical search depends on the objective of the analysis. However, in FLAC and other continuum-mechanics-based analysis procedures, FoS calculations result in a shear surface with the lowest FoS; and if the shear surface with the lowest FoS thus found is not of significance because of its size, location, or importance, it is difficult and of questionable value to reanalyze the problem for some other shear surface(s).

In the numerical assessment of the estimated slip surface at the Locke Island landslide, the item of greatest interest is the location of the shear surface with a FoS ≈ 1. In SSTAB2, the inferred shear surface geometry was analyzed first as a segmented (non-circular) shear surface and FoS result of 1.05 was obtained. Then a circular shear surface approximating the inferred shear surface was estimated manually and FoS of 1.11 was obtained. Then using the center of rotation of the manually estimated circular shear surface as a starting estimate and the accuracy limit of 30 m on the final location of center of circular shear surface, the critical circular search result of FoS = 1.01 was obtained. This shear surface approximates the inferred shear surface of Schuster et al. (1989) reasonably well. In FLAC analysis, the shear surface determined is small and is not comparable in size or location to that of Schuster et al. (1989). No attempt was made in analyzing the problem using FLAC for other shear surface(s).

The other item of interest at the Locke Island landslides was the magnitude of displacement of the landslide mass. Limit-equilibrium-based analysis procedures such as SSTAB2 are not applicable for calculating displacements. However, continuum-mechanics-based procedures, such as FLAC, are ideally suited for this purpose. For the 1973 ground surface, estimated ground water conditions and river water-surface elevation, and the circular shear-surface geometry with FoS = 1.01, the calculated displacement results at the toe of the sliding and rotating block using FLAC are: horizontal displacement toward the river = 125 m; vertical displacement = 1.75 m (upward). The upward vertical displacement at the toe was due to the sliding mass modeled as an elastic continuum and the shear surface modeled as an interface being circular. Schuster et al. (1989) had estimated that the toes of individual landslides in the Locke Island area had progressed as much as 150 m across the northeast channel of the Columbia River. These and other items of interest in the numerical assessment of Locke Island landslide at the cross-sectional locations marked on Fig. 6 are presented in Chugh and Schuster (2003).

CONCLUSIONS

In studying landslide problems with all their complexities, it is best to use observational skills to obtain the essential details of the problem. In this regard, the work of USGS (U.S. Geological Survey) personnel in dealing with the Locke Island landslides serves as an example worthy of serious study.

In numerical analysis of slope failures, finding a shear surface with the lowest FoS by back-calculation may not be meaningful; however, finding shear surface(s) with FoS ≈ 1 is meaningful. For this purpose, use of a limit-equilibrium-based solution procedure is superior to a continuum-mechanics-based solution procedure. Limit-equilibrium-based solution procedures offer the flexibility of computing FoS values for a large number of shear surfaces automatically via a search procedure and then identifying the shear surface with a FoS close to unity manually or via a set of program instructions. If for a given landslide problem of known geometry and best understood/estimated field conditions, this approach leads to more than one shear surface with a calculated FoS of one, or if all shear surfaces have a calculated FoS significantly greater than one, then the landslide geometry and/or field conditions need to be better understood. This observation also applies if the shear surface with a calculated FoS of unity significantly differs from the shear surface observed/estimated in the field. Continuum-mechanics-based procedures automatically result in a shear surface with minimum FoS and their usefulness in studying onset of ground instability may be limited. However, continuum-mechanics-based procedures provide the only means to calculate displacements – the other item of significant interest in studying landslides besides the onset of ground instability.

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