

**Seismic Re-Engineering of the Valdez Marine Terminal (VMT)  
Contract #556.08.01**

Prepared for

**The Prince William Sound  
Regional Citizen's Advisory Council  
(PWSRCAC)**

Prepared by

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The opinions expressed in this PWSRCAC-commissioned  
report are not necessarily those of PWSRCAC.

## EXECUTIVE SUMMARY

The primary purpose of the second phase of this study was to follow-up on the detailed analysis of rock slope stability for the VMT site conducted in 2006. Results of that study (West and Cho, 2007) indicated that rock slopes could become unstable under a combination of elevated pore pressures (high piezometer levels) and moderate earthquake shaking.

Terry R. West, Ph.D., P.E., geological and engineering consultant, met with the Joint Pipeline Office staff in Anchorage, and the staff of Alyeska, plus their consultants, in Valdez, during July 14-17, 2008. Following these discussions, more information was provided by Alyeska concerning the rock slopes: 1) a copy of the original slope design report of 1975 and 2) three figures from an internal report (Golder, Dam Report) on piezometric levels for a proposed dam across the quarry, which was not constructed. Also considered was a published paper by Major, Tart and Krantz, 2002. With the availability of these new data, Phase Two of the study was expanded to include an evaluation of the 1975 design report, further consideration of flag values, piezometer levels, rock bolt spacing, and concerns about through-going fractures in the rock slope.

The 1975 design report was analyzed (West and Cho, this report) and it was learned that zero pore pressures had been assumed in the design, based on the assumption that the slope would be completely drained. Consequently only seismic shaking was included in the design report and this was the only design conducted for any rock cuts at the VMT. The design report indicated that the PVR slope was stable using the designated bolt design and a seismic load of 0.6g, but a pore pressure of zero was assumed. This was a serious omission as the piezometers show a considerably high pore pressure in the slope. Also the slope analysis in the 1975 report assumed a block failure mechanism rather than using the fracture pattern of the rock mass, which is the current method of analysis now used.

Using the basic data from the design report and the same procedure, West and Cho (2008) recalculated the slope stability for the PVR slope. Based on current conditions of  $H_w/H = 0.8$ , a factor of safety of 0.94 was obtained for a 0.15g seismic event and 0.73 for 0.3g under the same pore pressure conditions.

Stability of the PVR slope was calculated in the 2007 report by West and Cho. This takes into account the fracture pattern of the rock mass as determined in the extensive field study. Results are provided in Table 3 of this report. A FS = 1.0 is obtained for  $H_w/H = 0.85$  for 0 g;  $H_w/H = 0.8$  for 0.1g and  $H_w/H = 0.55$  for 0.2 seismic shaking.

There is a concern about the piezometric levels for the PVR slope. Several values are above the flag levels established during construction. Also the three figures from the Golder, Dam report show a significant fluctuation in the levels over a two-year period. As the on-site piezometers are only read a few times per year, these values may not indicate the true range of water levels in the slope. Also the water levels could be higher between drain holes as a cone of depression exists relative to them much like that around a vertical water supply well. It is apparent that drainage of the rock slopes is difficult to accomplish as it was assumed that this could be done in 1975 but has not been accomplished to date.

Through-going versus continuous rock fractures were also considered. Two recent rock cuts in the Valdez area were examined, the slopes at the Valdez Ferry Terminal and the cut on the access road leading to the VMT site near the Solomon Gulch Dam. It is unlikely that a single fracture extends the full height of the slope but fractures tens of feet in extent are visible.

The following recommendations are made. Alyeska should consider the initiation of an up-to-date analysis of the critical rock slopes at the VMT site. The 1975 report design did not include details of the slope fractures or discontinuities that control stability or consider both pore pressures and seismic shaking. Also, additional methods to accomplish slope drainage to lower the piezometric level in the slopes should be considered. Lastly, provisions should be made for critical slopes to contain all fallen rock blocks within an area near the slope base.

## **Abbreviations**

A: Earthquake Acceleration

Ah: Horizontal Earthquake Acceleration

Av: Vertical Earthquake Acceleration

BLM: The Bureau of Land management

FS: Factor of Safety

H: Height of Slope

Hw: Height of Water

JPO: The Joint Pipeline Office

Kips: 1000 pounds

PVR: Power Vapor Recovery

PWSRCAC: The Prince William Sound Regional Citizen's Advisory Council

TAP: The Trans-Alaska Pipeline

VMT: Valdez Marine Terminal

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## INTRODUCTION

The second phase of this work was initiated May 1, 2008 to follow up on the extensive field and office study conducted in 2006 (West and Cho, 2007) on the Valdez Marine Terminal. This first study involved a detailed analysis of the rock slope stability for the site. The Executive Summary for that report and the table of data compiled by PWSRCAC on slope stability are included in Appendix A of this current report.

The initial purpose of the second phase of work was to determine the extent to which Alyeska had considered the recommendations of the 2007 report. On July 14-17, 2008 Terry R. West, Ph.D., P.E., geological and engineering consultant, visited Anchorage and Valdez, Alaska to meet with the Joint Pipeline Office in Anchorage and Alyeska at the VMT site in Valdez. A copy of the trip report for the July 14-17, 2008 site visit is enclosed as Appendix B. During the Anchorage visit Terry West and Tom Kuckertz met with Joe Dygas, Doug Lalla, and Nolan Heath from JPO/BLM.

During the VMT site visit in July, the following individuals were present: Terry West and Tom Kuckertz from PWSRCAC, Rhonda Williams from BLM/JPO, Barry Roberts, Laura Meadors and Greg Kinney from Alyeska, and Bucky Tart and Graeme Major from Golder and Associates. Dr. West began the meeting by discussing the Executive Summary and table of slope stability data (see Appendix A). Dr. West indicated that the rock slopes could become unstable under a combination of elevated pore pressures (high piezometer levels) and moderate earthquake shaking.

In response to this information, the Golder Consultants stated that both pore pressure and seismic shaking had been considered in the design for the Power Vapor Recovery (PVR) slope

which had originally failed during construction and was subsequently regraded and rock bolted. By the end of the day, Alyeska provided a copy of the original slope design report of 1975. The complete citation for this report is provided in the reference section at the end of this final report.

Responding to the inquiry about piezometric data, Bucky Tart volunteered that a detailed study had been conducted for the design of the proposed dam to be built across the quarry. This project was not implemented and the report has not been released to the public. However, subsequent to Dr. West's visit, three figures from that report related to the piezometric study, were provided to Dr. West by Alyeska. These three are included in Appendix C of this report.

A final point of discussion about the rock slopes was raised by Graeme Major. He stated that the fractures in the rock slopes were not necessarily through-going but, could instead, be discontinuous. This concept had been addressed in the West and Cho report (2007) and is a common consideration in rock slope stability evaluations. Only a small amount of intact rock, with its much greater strength than that of sliding friction, will significantly increase the factor of safety of a rock slope. See the paper by West, 1996 provided in the reference list. Dr. West indicated that fracture surfaces of significant length and area can be observed in the recent rock cuts in the Valdez area. This subject is considered further in the subsequent discussion.

As a direct response to other recommendations from the West and Cho (2007) report, the following was noted by Alyeska and Golder Associates. The drain holes are checked regularly and cleaned out when sediment collects in them. Rock bolts are re-tensioned, replaced and added as needed during scheduled maintenance periods for the rock slopes. This is accomplished every four years or so. The next scheduled maintenance period is 2009. As built drawings showing locations of rock bolts and drain holes were not available. Information was later provided on the initial bolt spacing for the PVR slope. It was also learned that the only

rock slope design conducted at the VMT was for the PVR slope in 1975. For the other slopes, the same design criteria were applied, with the assumption that the rock conditions were sufficiently similar that this analysis was appropriate for the other slopes.

Piezometric levels and flag levels were discussed. The flag levels for piezometers were established soon after construction. Subsequent pore pressures or piezometric levels were compared to these flag values. The assumption seems to be that if the slopes were stable at the flag levels following construction, they would continue to be stable thereafter if these elevations were not exceeded. Data on these flag values became available during the analysis portion of this current study.

Dr. West also mentioned the lack of a contingency plan by Alyeska to address a rise in the piezometric levels relative to the flag values. Golder and Associate representatives indicated that they would recommend the installation of more drainage holes if the piezometric levels rose significantly above the flag values.

Based on the discussion provided above, it became abundantly clear that the objectives for this second phase of study had been greatly expanded. It had been planned that the second phase would involve a small report listing the ways in which the recommendation of the West and Cho report, 2007 had been considered. Instead, this was now expanded to include an evaluation of the 1975 design report, further consideration of flag values, piezometer levels, rock bolt spacing, and concerns about through going fractures in the rock slopes. All of these items are addressed in the following report.

## EVALUATION OF DATA

### A. Review of two reports on the PVR site

Two reports that became available for the first time to Drs. West and Cho were the following:

1) Alyeska Pipeline Service Company, “Design Considerations for the Rock Slope at the Powerhouse and Vapor Recovery Building, Valdez Terminal”, December 1975 and 2) Major, Graeme, Tart, Rupert G. Jr and Krantz, Deborah J. (2002). “Performance of the PVR Rock Slope at Valdez Marine Terminal”, Cold Regions Engineering, in Cold Regions Impacts on Transportation and Infrastructure, May 20-22, Anchorage, AK. In addition, as stated previously, Figures 1, 2 and 3 were made available from the design report for the proposed dam construction at the quarry. These are provided here in Appendix C. Figure 1 shows a map and cross section location extending from the PVR Slope to the Quarry site. Figure 2 is a cross section showing the piezometer locations for the dam site and PVR slope, and Figure 3 shows the water level fluctuations over a period of two years for the three nested piezometers at the proposed dam site.

1. Design Considerations for the Rock Slope at the Powerhouse and Vapor Recovery Building, Valdez Terminal, December 1975.

In this analysis, a slope face of  $48^\circ$  was considered with a fault dipping outward at  $16^\circ$  to form the base and a tension fracture dipping at  $50^\circ$  outward to form the backside of the block. The friction value for the fracture was  $27^\circ$  and  $35^\circ$  for the fault. The slope was analyzed by using a series of blocks with thicknesses from 25 to 90 feet. This yielded 7 cases that were analyzed individually. Calculations were made considering seismic loads of 0g and 0.3g for all cases plus 0.6g for the 25 foot thick block. Varying bolt forces were applied and the force required for stability at 0.3g was calculated. It should be noted that pore water or piezometric pressure was not considered, that is,  $H_w/H$  for the slope was set equal to zero. To quote the design report on page 18 under Interactive Graphics .... “In all cases it was assumed that the drainage program was completed enough that pore pressures were not taken into account, the shearing friction along foliation planes was assumed to be

27° and along the fault was 35°...”. These documents that only seismic loading was considered and pore pressure was not included in this analysis.

Figures 37 and 38 of the report involve a block thickness of 90 feet. Figure 37 is for the dry case and Figure 38 considers a pore pressure situation with  $H_w/H \approx 0.9$ . The calculations for this pore pressure case indicate a movement of 20 inches without any bolt support. This is excessive movement and indicates a failure condition.

In summary, pore pressures were assumed to equal zero for the 7 primary cases considered. The slope were found to be stable under 0.3g with bolts depending on the bolt capacity applied, unstable both under 0.3g without bolts and 0.6g with bolts. Only in the final calculation was pore water pressure considered and this was found to yield excessive movement that would cause instability. Pore pressure for this final case was approximately  $H_w/H = 0.9$ .

2. Performance of the PVR Rock Slope at Valdez Marine Terminal (2002) by Major, Tart and Krantz, Cold Regions Impacts on Transportation and Infrastructure, May 20-22, Anchorage AK.

This paper was obtained from the published literature. It contains useful information about piezometer readings at the PVR site. Figures 7 and 8 for 1999 show that the average pore pressure conditions for the two cross sections was  $H_w/H = 0.8$ . This can be used to recalculate the stability of the PVR as considered in the 1975 design document. The same values for parameters in that report are considered in this follow up analysis performed by West and Cho for the current study.

Using  $H_w/H = 0.8$  and 0.3g the calculated Factor of Safety (FS) = 0.73. This includes the bolt support as considered above. Additional calculations were made assuming different pore pressures and different seismic loadings. Table 1 is a summary for the FS values under different conditions. Note that the current situation with  $g=0$  and  $H_w/H = 0.8$ , yields a FS=1.28. A critical

value of 0.94 (<1.0) would occur with  $H_w/H=0.8$  and  $g=0.15$ . The complete analysis showing these calculations is provided as Appendix D to this report.

Table 1 from Major et al., 2002, provides additional, valuable information. It is reproduced here as Table 2. Thirteen piezometers for the PVR slope are included for September, 2000. A comparison is made to the Flag level for each piezometer. Four of the piezometers showed a significant increase in elevation: For Numbers 40, 47, 49 and 50 the increase was 2, 11, 6 and 5 feet respectively. These four piezometers ranged from 0.3 to 9.1 feet above the flag value established in September 2000. The current status of these piezometer levels has not been compiled by Drs. West and Cho, although these data are apparently available in the piezometer reports for Alyeska authored by Golder and Associates.

Table 1. Stability Analysis, PVR Slope, West and Cho (2008); Based on 1975 Design Details.

Conditions	Pore Pressure ( $H_w/H_{slope}$ )	Earthquake ( $a_h$ )	FS
Current 1	0.8	0	1.28
Current 2	0.9	0	1.03
Dry 1	0	0	2.92
Dry 2	0	0.3	1.52
Dry 3	0	0.6	0.81
Saturated 1	1	0	0.84
Saturated 2	1	0.3	0.52
Critical 1	0.8	0.15	0.94
Critical 2	0.8	0.3	0.73

B. Comparison of Results Between 1975 Design Report and West and Cho Report, 2007.

A summary of the results of the slope stability analysis by West and Cho (2007) is given in the Executive Summary and in the comparison table compiled by PWSRCAC included in Appendix A of this report. The analysis is based on an extensive field investigation used to measure the fracture pattern found in the rock slopes at the VMT site. Analysis includes both

Table 2. From Table 1, Major, Tart and Krontz, 2002.

Piezometer Number	Elevation Head (ft)	Pressure Head (ft)	Total Head (ft)	Flag Level (ft)	Flag Level minus Head (ft)	Change since Pre-1984 Readings (ft)
36	467.8	28.3	496.1	504	7.9	1
37	441.9	77.6	519.5	522	2.5	1
40	390.3	60.0	450.3	450	(0.3)	2
41	384.5	82.2	466.7	470	3.3	1
42	377.7	75.0	452.7	465	12.3	(8.0)
43	381.4	42.6	424.0	430	6.0	0
44	360.9	35.4	396.3	400	3.7	7
45	358.2	3.1	361.3	410	48.7	1
46	361.0	28.2	389.2	390	0.8	6
47	338.7	130.4	469.1	460	(9.1)	11
48	371.6	11.7	383.3	390	6.7	0
49	337.9	43.7	381.6	380	(1.6)	6
50	328.5	54.8	383.3	380	(3.3)	5

pore pressure effects and seismic loading and involves an analysis based on the fracture pattern. By contrast, the 1975 Design Report used a block-shaped failure body bounded by a low angle fault dipping at 16° into the opening and bounded in back by foliation planes at different distances into the face that dip inward at 50°. The West and Cho analysis (2007) concludes that rock wedges dipping into the opening are subject to failure, rather than the block-shape body assumed in the 1975 Design Report. Careful consideration of the geometry leads to the conclusion that failure by dipping wedges is a much more likely failure mode than that assumed in the 1975 Design Report. Common rock slope failures are presented in Appendix F. Planar failures require release planes to isolate the blocks so they can slide. Wedge planes outline the block and no other failure planes are required. As pointed out in the previous discussion, complete drainage yielding no pore pressure effects was assumed in all but the last analysis, to determine slope stability. In that last case, pore pressures were assumed but a full analysis of seismic loading and rock bolt support was not included.

A comparison calculation for the PVR slope is provided in Table 3. The Alyeska, 1975 Design report is compared item by item with the analysis in the West and Cho, 2007 report. Note the different mode of failure assumed between the two analyses. Wedge failure rather than planar failure is much more likely. This conclusion is based on field measurements of the fracture pattern at the VMT site. The fault and foliation failure mode of the 1975 design report is a much less credible mechanism. In the West and Cho report, 2007, failure is predicted to occur (FS=1) under the following conditions: 0.85-Hw/H under 0.0g; 0.8-Hw/H under 0.1g and 0.55 Hw/H under 0.2g. In addition, Case 4 of the 1975 Design report has been recalculated in this report and presented in Table 1. Next using the slope parameters from the Alyeska Design Report slope stability was calculated using the basic equation for planar failure assuming an active rock bolt force (modified from Cho, 2002).

$$FS = \frac{cA + \{W[(1-k_v)\cos\theta - k_h \sin\theta] - V \sin\theta - U + T \sin(\beta + \theta)\} \tan\phi + T \cos(\beta + \theta)}{W[(1-k_v)\sin\theta + k_h \cos\theta] + V \cos\beta}$$

c = Cohesion

$\phi$  = Friction angle of failure surface

A = Area of failure plane

W = Weight of block

T = Tension in bolts or cables

U, V = Water pressure

$k_h$  = Horizontal pseudostatic coefficient

$k_v$  = Vertical pseudostatic coefficient

$\theta$  = Inclination (dip) of failure plane

$\beta$  = Inclination of rock bolt from horizontal

Details of this calculation are provided in Appendix D.

This indicates that the slope would become unstable under the current pore pressure conditions with the onset of earthquake loading = 0.15g.

Table 3. Comparison for PVR Slope Stability Analysis Between Alyeska Report, 1975 and West and Cho Report, 2007.

Items	Alyeska, 1975	West & Cho, 2007	Remarks
Slope Height (ft)	120 ft?	115 ft	Height varies across the cut
Cut slope dip angle	48°	64°	Angle varies across the cut
Discontinuities considered	High angle foliation + low angle fault	Daylighting joints	The cut was regraded along foliation after failure
Fracture continuity	Through-going	Through-going	
Dip angle considered	Foliation: 50° Fault: 16°	60°	Foliation dip angle changes slightly across the cut (47-60° by Golder)
Friction Angle	Foliation: 27° Fault: 35°	39°	
Cohesion	0	0	
Water Level	Manual calculation includes piezometric level, inclusion of piezometric levels not included for interactive software solution	Applied dry Hw/H=0 to fully saturated Hw/H=1 joint	Water level changed seldom more than a few feet over 20 feet (Golder's paper). There appears to be a trend of slow increase near base. *0.9 Hw/H based on paper by Graeme Major, Rupert Tart, and Deborah Krontz (read off from cross sections)
Earthquake Acceleration	A=0, 0.3, 0.6g	A <sub>h</sub> = 0, 0.3, 0.5, 0.7 A <sub>v</sub> = 0, 0.5a <sub>h</sub>	Design Manual for pipeline (TAPS): - Richter Magnitude = 8.5 - Design Contingency Acceleration = 0.6g
Bolt Capacity	100 kips per bolt	100 kips per bolt	Capacity may decrease with time
Bolt Spacing	10 ft spacing for 11 rows, 5 ft spacing for bottom 3 rows per 10 ft width	Assumed 4 bolts per unit width	30 ft long
Bolt inclination	Horizontal and at 40°	Added T to resisting force without subtracting T term from driving force	
Failure Type	Planar slab failure from combination of foliation and fault	Planar from daylighting joints, wedge with 2 steep-angle joints	Planar: Stable Wedge Failure: likely to occur More likely fractures will control failure rather than fault and foliation (Alyeska Report)

Items	Alyeska, 1975	West & Cho, 2007	Remarks
Failure Occurrence	Pseudostatic: stable under 0.3g with bolt depending on the bolt capacity applied, unstable 0.3g without bolt or 0.6g with bolt. Newmark displacement: 0.6g would cause 6-9 inch movement, but not large enough for static instability	0.85=Hw/H under 0.0g 0.8=Hw/H with 0.1g 0.55=Hw/H with 0.2g	
Analytical tool	Interactive software plus graphic manual method	Excel spreadsheet	Wedge failure analysis considering bolts, water, and earthquake effects accomplished by West & Cho, but not considered by Alyeska, 1975.
Output	Calculated using bolt capacity assuming two accelerations (0.3g, 0.6g). Pore pressure conditions not clearly stated, displacement calculations made.	Calculated pore pressure level, (Hw/H) needed, with and without acceleration to cause failure.	West & Cho calculated FS as an example of slope geometry (case 4 Aleyska Repot, 1975) and found that FS equals 0.73 under 0.3g and 0.8 Hw/H conditions.

### C. Pore Pressure/Piezometer Fluctuations

Data on the piezometers at the proposed dam site were provided to Dr. West following the July 2008 meeting with Alyeska at the VMT. These three figures are provided in this report in Appendix C. Figure 3 shows a fluctuation from 6 to 8 feet between October 2004 until October 2006 or a period of two years. The shallowest piezometer showed a variation of almost 5 feet and the deeper two piezometers showed a variation of between 6 and 7.5 feet. This is important information because the piezometers in the PVR slope are read only once or twice per year and annual fluctuation is not represented. This suggests that the annual fluctuation in the PVR piezometers could be as much as 5 feet.

### D. Through-going versus discontinuous fractures.

Another point raised during the discussion in July 2008 at the VMT meeting involved whether the fractures in the rock mass at VMT were through going or discontinuous. This aspect is commonly considered in rock slope stability analysis and it was addressed previously in the publication by West (1996). It is well known that only 1 or 2% of intact rock along the fracture surface can increase slope stability in a significant way. During the July 2008 visit, Dr. West re-examined the recent cut slopes in the Valdez area. These same slopes were examined during the field investigation in the summer, 2006. The extensive rock cuts behind the Ferry Terminal were examined in 2008 and photographed. Several joints and fractures show lengthy extensions of  $\frac{1}{2}$  the height of the slope for lengths well over 10 feet in extent. The recent rock cut on the access road to the VMT site near the Solomon Gulch Dam was also examined and photographed. Lengthy extensions well over 10 feet in extent were noted in this cut as well. Photographs of these two localities are provided as Appendix E of this report.

In the paper by Major, et al. 2002 piezometric pressure and flag levels are discussed under the heading of Flag Criteria. With limited drainage from the slopes through drain holes

(hence the high piezometric levels) the authors suggest that the joints are discontinuous. Low drainage flows are also quoted as being an indication of limited connectivity of the fractures. Those authors also suggest that pore pressures would be relieved locally which would minimize the hydraulic uplift on the rock mass. The authors of the current report (West and Cho, 2008) have several different points of view in this regard than do the authors of the report by Major, et al. 2002. Large volumes of drainage water are not needed to reduce uplift pressures in a rock mass. What is required is to break the continuous column of water that provides hydrostatic or uplift pressure. Small volumes of flow from drain holes can be quite effective, if this reduces the uplift pressure when fracture saturation is disrupted.

Also the fractures need not be through going for the entire slope to yield a local failure, but only over the distance of a failure block. Fractures must also be connected in some way to the piezometric level shown for the slope.

A final consideration is that pore pressure in a slope can be considerably greater between drain holes. There is a cone of depression effect around a nearly horizontal drain hole much as there is one around a vertical water supply well (Cook et al., 2008). This suggests that the pore pressure in some parts of the rock slope will significantly exceed those values shown by the piezometers.

## SUMMARY

1. Terry R. West, Ph.D., P.E., CPG met at the Joint Pipeline (JPL) Office and at the Alyeska, Valdez Marine Terminal (VMT) in a trip to Anchorage and Valdez, Alaska respectively on June 14-17, 2008. At the JPL office those in attendance were Terry West and Tom Kuckertz from PWSRCAC, and Joe Dygas, Doug Lalla and Nolan Heath from JPO/BLM and at the VMT those in attendance were Terry West and Tom Kuckertz from PWSRCAC, Rhonda

Williams from BLM/JPO, Barry Roberts, Laura Meadors and Greg Kinney from Alyeska, and Bucky Tart and Graeme Major from Golder and Associates. A copy of the site visit report is enclosed as Appendix B. Appendix A contains the Executive Summary of the West and Cho, 2007 report, and a table of stability data for that study.

2. Dr. West indicated that the rock slopes could become unstable under a combination of elevated pore pressure (high piezometric levels) and moderate earthquake shaking. In response, Golder Consultants stated that both pore pressure and seismic shaking were considered in the design of the Power Vapor Slope (PVR) that had failed in 1975 during excavation of the rock slopes in 1974. This was the only rock slope design performed at the VMT site. The same criteria (length or bolts and spacing) were applied to the other slopes, the assumption being that rock conditions for the other slopes were sufficiently similar so that this analysis was appropriate. A copy of the design document was provided to Dr. West for the first time during the meeting, its title being, Alyeska Pipeline Service Company, Design considerations for the Rock Slope at the Powerhouse and Recovery Vapor Building, Valdez Terminal, December, 1975.
3. Responding to the concern about high piezometric levels, Bucky Tart volunteered that a detailed piezometer study had been conducted for the design of a proposed dam across the quarry. As subsequent dam construction was not approved, the report was not released to the general public. Following the meeting, Alyeska made three figures from the piezometric study available to Dr. West for evaluation. These are included as Appendix C.
4. Several points of discussion were raised by Graeme Major from Golder and Associates. He questioned whether the fractures in the rock slope were through going or not. This concept was addressed in the West and Cho report (2007) and the concept is well known to Dr. West (see West, 1996 for details). A small amount of intact rock is known to significantly increase

the stability of a rock slope. Dr. West did point out that the recent cut slopes in the Valdez area (Ferry Terminal and rock cut on the access road to VMT near the Solomon Gulch dam outlet) had extensive fractures extending 10 or more feet.

5. The report by West and Cho (2007) had indicated a concern that the drain holes in the slopes needed to be cleaned out regularly. The response was that the drain holes are inspected routinely and sediments cleaned out as necessary. Rock bolts are retensioned, replaced and added as needed during scheduled maintenance periods of every four years or so. The next one is scheduled to be performed in 2009.
6. Flag levels were discussed. These are the desired piezometric levels established after the drainage holes were installed. The assumption seems to be that if the slopes were stable at these levels following construction they would continue to be stable in the future if the elevations are not exceeded. There is a concern in this regard; it does not take seismic loading into consideration.
7. There is a need for a contingency plan to deal with rising piezometric levels if this should occur. In response to this the Golder and Associates representatives indicate that more drainage holes would be drilled if this were to develop. However, experience at the site has shown that it is very difficult to accomplish slope drainage by simply adding more drain holes. An intricate network of fractures may make it difficult to intercept enough of them to provide adequate water drainage.
8. Based on the new material provided in response to the inquiry at the meeting, the scope of the work for this West and Cho study had been significantly expanded in order to review and evaluate this new material. This report is therefore much more extensive than was first envisioned.

9. The first part of this extended analysis involved the Design Considerations for the PVR Rock Slope at VMT, 1975. In the report a rock slope face of  $48^\circ$  was considered with a fault dipping outward at  $16^\circ$  to form the base of the failure block with a friction value of  $35^\circ$ . The block was bounded by a fracture dipping at  $50^\circ$  outward, parallel to the foliation of the rock mass. Seven individual cases were analyzed with block thicknesses ranging from 25 to 90 feet (into the slope). Seismic loads of 0 and 0.3g for all cases, plus 0.6g for the 25 foot thick block, were considered. Bolt forces were applied and stability was indicated for 0 and 0.3g but instability occurred at 0.6g. It should be noted that zero pore pressure was considered in the 1975 design as it was assumed that the slope would be fully drained by the drain holes. The 1975 report on page 18 states that pore pressures were not taken into account. Finally a block 90 feet thick was considered with a pore pressure of about  $H_w/H=0.9$ . Excessive movement and failure were indicated under these conditions. A complete example showing both pore pressure and seismic shaking was not included. Based on a review of the design document by West and Cho (this report) it is concluded that only seismic loading was evaluated in the design, and pore pressure was omitted or assumed to equal zero.
10. Basic data for the VMT slope were obtained through a review of the paper by Major, Tart and Krontz, 2002, "Performance of the PVR Rock Slope at Valdez Main Terminal, Cold Regions Impacts on Transportation and Infrastructure", May 20-22, Anchorage, AK. Examination in this paper indicates that on average  $H_w/H$  for the PVR slope = 0.8. This can be used to recalculate the stability of the PVR slope as considered in the 1975 design document. Using  $H_w/H = 0.8$  and 0.3g seismic loading, a Factor of Safety = 0.73 is obtained. Table 1 in the current report is a summary of FS values under different conditions. Note that under the existing condition of  $H_w/H = 0.8$  and  $g=0$ , a  $FS=1.28$  is obtained. With this pore pressure in effect and  $g=0.15$ , it yields  $FS=0.94 (<1.0)$  or an unstable situation. For a

saturated condition,  $H_w/H=1.0$  with  $g=0.30$ , a  $FS=0.52$  is obtained. This clearly indicates that for the current piezometric levels only moderate seismic loading could cause an unstable condition.

11. A major concern about the piezometer levels is observed by an examination of Table 1 from Major, et al., presented here as Table 2. This shows that several of the piezometers in the PVR slope are now above the flag levels, one being 9.1 feet higher. Another concern is shown in Appendix C, the three figures made available from the Dam Design report provided to Dr. West by Alyeska following the July 2008 visit to the VMT. Figure 3 in Appendix C shows a change in water level of as much as 5 feet for the piezometers within a two year period. Piezometers at the VMT site are not read continuously but only several times per summer. It seems reasonable that these piezometers could vary by up to five feet in a year's time. A combination of increased values in the PVR piezometers (Major, et al., 2002) and the sizeable annual fluctuation (Golder, Dam Report, Tables 1-3) indicates a concern that the pore pressures could easily exceed the 0.8 to 0.9 values shown for the slope in the various publications and calculations. Also, piezometric levels could be much higher between the drain holes as a cone of depression occurs around such borings, much like that around a vertical, pumping well (Cook et al., 2008).

12. Table 3 of this report is a detailed comparison on the analysis of the PVR slope between the results of the Design Report by Alyeska and the analysis of that slope based on the West and Cho (2007) field study and analysis. The West and Cho report, 2007 considers both pore pressure effects and seismic loading. The mode of failure is based on the rock fracture pattern as determined by field study and it considers that the mode of failure involves rock wedges that dip into the opening. This is a much more realistic failure mechanism than is the fault, and block-shaped feature assumed in the Design Report, 1975. The best analysis information

for the PVR slope stability is given in the FS column of Table 1 and the West and Cho, 2007 Failure Occurrence Category, Table 3 (page 9) third column. This is for FS=1.0. Without earthquake shaking under the current pore pressure conditions, the FS for the PVR slope lies between 1.03 and 1.28. However, as shown in Table 1, only a seismic load of 0.15g could reduce the FS to below 1.0.

13. The concept of through-going versus discontinuous rock fractures is also considered. It is highly unlikely that a single fracture extends the full height of the slopes, 115 feet, but fractures tens of feet in extent are visible in the fresh rock excavations in Valdez. It is clear that a sizeable block of rock coming from between the 10 foot or 5 foot bolt spacing in the slope, could be liberated under a combination of high pore pressure and moderate seismic loading.
14. It is apparent that drainage of the rock slope is difficult to achieve at the VMT site. The designers of the 1975 report assumed that the pore pressures would be reduced to zero by the drainage system and thus these pressures were not considered in the design. This obviously was not achieved. If the flag levels are significantly exceeded in the future it may prove quite difficult to lower the piezometric values with further drainage. For this reason it is imperative that Alyeska continues to route surface water away from the rock slopes at the VMT facility to minimize infiltration into the slopes.

## RECOMMENDATIONS

1. Alyeska should consider initiating an up-to-date analysis of rock slope stability for the critical slopes of the VMT site. The design performed in 1975 did not consider the actual details of the discontinuities in the slope and did not take into account both pore pressures and seismic shaking. There may have been a subsequent analysis based on Bukovansky's report (1990),

which was considered by West and Cho (2007), but discontinuity data and calculations were not included in the portion provided.

2. Additional methods to accomplish slope drainage to lower the piezometric levels in the slopes should be considered. Experience has shown that the drain holes placed to date have not been effective in reducing the elevations below the flag levels. It may prove helpful to orient drain holes in a direction perpendicular to the main fractures. Under moderate earthquake shaking,  $g=0.15$  an unstable condition is indicated. At full pore pressure level  $H_w/H=1.0$ , and  $g=0.30$ , a  $FS=0.52$  is obtained.
3. Provisions should be made to contain any fallen rock blocks, with dimensions less than the bolt spacing, to an area adjacent to the base of the rock slopes in critical areas.

## REFERENCES

- Alyeska Pipeline Service Company, Design Considerations for the Rock Slopes at the Powerhouse and Vapor Recovery Building, Valdez, Terminal, December 1975.
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- Cho, K.H., 2002, Deterministic and Probabilistic Analysis of Rock Slope Stability under Earthquake Loading Conditions, Ph.D. thesis, Purdue University.
- Cook, D.I., Santi, P.M. and Higgins, J.D., 2008, Horizontal Landslide Drain Design: State-of-the-Art and Unanswered Question, Environmental & Engineering Geoscience, Vol XIV No.4. 241-250.
- Major, G., Tart, R.G. and Krantz, D., 2002, Performance of the DVR Rock Slopes at Valdez Marine Terminal, Cold Regions Engineering, in Cold Regions Impacts on Transportation and Infrastructure, May 20-22, Anchorage, AK.
- West, T.R., 1996, The Effects of Positive Pore Pressure on Sliding and Toppling of Rocks with some Consideration of Intact Rock Effects, Environmental & Engineering Geoscience, Vol. II, No.3, 339-353.
- West, T.R. and Cho, K.H., 2007, Rock Slope Stability of the VMT.

## APPENDICES

- A. Executive Summary and Table of Slope Data, from report by West and Cho, 2007.
- B. Field Trip Report by Dr. T.R. West, Visit to Anchorage and Valdez, Alaska, including VMT Site, July 14-17, 2008.
- C. Figures 1-3 from Design Report, Proposed Dam Across the Rock Quarry, at VMT, by Golden and Associates, 2006 ??
- D. Stability Analysis, PVR Slope, Factors from 1975 Design, Recalculated by West and Cho, 2008.
- E. Photographs, Fresh Rock Cuts, Valdez Area, Showing Extensive Fracture Surfaces.
- F. Four Types of Rock Slope Failures, from report by West and Cho, 2007

Appendix A. Executive Summary and Table of Slope Data, from report by West and Cho, 2007.

## EXECUTIVE SUMMARY

The primary purpose of this project was to evaluate the stability of rock slopes of the VMT during potential earthquake conditions. Field reconnaissance and a detailed fracture survey of the rock slopes were conducted by Dr. Terry R. West and his associates in July and August 2006.

During the fracture survey more than 300 discontinuity values were measured in the field. The discontinuity data were measured on those relatively critical slopes including the Ballast Water Treatment Plant (“BWT Slope”), the Power House and Vapor Recovery Plant (“PVR Slope”), the West Manifold Building (“WM Slope”), the West Tank Farm Slope (“WTF Slope”), and the East Tank Farm Slope (“ETF Slope”). Discontinuity data were also obtained from the less critical slopes including the Power House Road Slope, the Tea Shelter Slope, and the rock quarries located on the southern portion of the VMT site.

Using these fracture data and existing rock cut information available at the time of this investigation, an analysis of rock slope stability was conducted using kinematic and factor of safety (deterministic) methods. Because of the uncertainty of the information, the probability of failure method was also employed to evaluate the stability of the VMT slopes in this study. Assumptions concerning rock mass strengths were made based on the literature and experience of the authors.

Based on the kinematic and kinetic analyses, it is anticipated that the external loading conditions equal to  $0.7H_w/H_{\text{slope}}$  or equal to pore pressure of  $0.6H_w/H_{\text{slope}}$  with 0.1g of horizontal acceleration will cause the BWT Slope to become unstable. For the PVR Slope, the external loading conditions equal to  $0.85H_w/H_{\text{slope}}$  or equal to pore pressure of  $0.8H_w/H_{\text{slope}}$  with 0.1g of horizontal acceleration or  $0.55H_w/H_{\text{slope}}$  with 0.2g of horizontal acceleration may cause the PVR Slope to become unstable. For the West Manifold Slope, the external loading conditions equal to  $0.35H_w/H_{\text{slope}}$ , and the external loading conditions equal to pore pressure of  $0.15H_w/H_{\text{slope}}$  with 0.1g of horizontal acceleration may cause the West Manifold Slope to become unstable. For the East Tank Farm Slope, the external loading conditions equal to  $0.7H_w/H_{\text{slope}}$  or the external loading conditions equal to pore pressure of  $0.45H_w/H_{\text{slope}}$  with 0.1g of horizontal acceleration may cause the East Tank Farm Slope to become unstable. For the West Tank Farm Slope, the external loading conditions equal to  $0.65H_w/H_{\text{slope}}$  or the external loading conditions equal to pore pressure of  $0.5H_w/H_{\text{slope}}$  with 0.1g of horizontal acceleration may cause the East Tank Farm Slope to become unstable. Details concerning drainage holes at VMT were not provided for this study. These data are required along with rock bolt distributions in order to perform a more precise evaluation of slope stability for the site.

To reduce the risk of the existing slopes at this time, the ditches above the rock slopes should have steep enough grades to avoid water-ponding to prevent infiltration of ponded water which can increase pore pressures. Also, it is recommended that any cracks at the top of the slope be sealed with grout or asphalt. It is also recommended that the piezometers which are clogged in the VMT slopes be regularly cleaned and measured frequently to monitor pore pressures. It is also recommended that more rock bolts be installed in the areas where the existing rock bolts are loosened and where rock bolts have not been installed following a further study to establish these details. Finally, a contingency plan should be developed to address an increase in pore pressure due to increased precipitation, as higher pore pressures could lead to slope instability.

# West and Cho Report Findings: Slopes May Become Unstable under Following Conditions

Slope	Pore Pressure ( $H_w/H_{slope}$ )	Accel (g)	Comment
BWTF	0.7	0.0	No quake
BWTF	0.6	0.1	
Pow Vapor	0.85	0.0	No quake
Pow Vapor	0.8	0.1	
Pow Vap	0.55	0.2	
W Manifold	0.35	0.0	No quake
W Manifold	0.15	0.1	
E T Farm	0.7	0.0	No quake
E T Farm	0.45	0.1	
W T Farm	0.65	0.0	No quake
W T Farm	0.5	0.1	

9/20/2007 Board Meeting

Appendix B. Field Trip Report by Dr. T.R. West, Visit to Anchorage and Valdez,  
Alaska, including VMT Site, July 14-17, 2008.

Trip Report by Dr. Terry R. West  
Geological and Engineering Consultant  
Anchorage & Valdez, Alaska  
July 14-17, 2008

Anchorage, July 14

Dr. Terry West and Dr. Tom Kuckertz met on Monday morning for breakfast to plan the day's activities. We stopped first at the RCAC building in Anchorage for T.R. West to meet the office staff before meeting with personnel in the Joint Pipeline Office. At that meeting five members were present: Terry West, consultant for RCAC, Tom Kuckertz with RCAC and Joe Dygas, Doug Lalla and Nolan Heath from JPO/BLM.

Dr. West provided them with summary information regarding the report "Rock Slope Stability of VMT" by West and Cho, dated September 2007. Included was the one page Executive Summary of the report and a one-page table prepared by RCAC showing stability conditions for five primary slopes at VMT. These data showed results without earthquake loading and under seismic conditions of 0.1 or 0.2 g accelerations. They depicted conditions at which the factor of safety became equal to one.

Dr. West explained that according to the results of the study, a combination of high pore pressure and moderate shaking would reduce the factor of safety below one for all the slopes. The question posed was: Is there a concern by JPL regarding this analysis that shows unstable conditions for the slopes under certain conditions? Several assumptions were made when performing the stability calculations. Included were bolt spacing, friction values and through-going characteristics of the individual fractures. These same concerns will be discussed tomorrow at VMT with Alyeska and Golder personnel. Joe Dygas decided to have a JPL representative present during the meeting at the VMT.

Beginning in midmorning Tom Kuckertz drove Dr. West to Valdez from Anchorage via the Glenn and Richardson Highways. We had a late lunch near Glennallen and arrived in Valdez about 6PM in the evening.

Valdez, July 15

Terry West met Tom Kuckertz at the RCAC office at 7:15AM to make additional copies of the two handouts used yesterday, to be distributed at the VMT meeting. This was the Executive Summary and the table of data depicting the conditions that would yield a slope failure for the five primary slopes. We traveled to the VMT site, checked through security and proceeded to the headquarters building for VMT. We met in the second floor conference room. Eight individuals were present for the meeting. Terry West and Tom Kuckertz from RCAC, Rhonda Williams from BLM/JPO, Barry Roberts, Laura Meadows and Greg Kinney from Alyeska, and Bucky Tart and Graeme Major from Golder and Associates.

Dr. West began the discussion by passing out the two summary papers and discussing their significance. It was pointed out that under pore pressure conditions and moderate earthquake shaking that the slopes would become unstable. The size of blocks would likely be less than the rock bolt spacing or 5 feet. However, some bolt spacing is at 10 feet and other slopes do not contain any rock bolts.

Dr. West requested information on the piezometric levels in the slope so the pore pressure data could be compared to the water elevations assumed in calculations presented in the report. The most recent report on piezometer levels at VMT was provided before day's end. Dr.

West asked if the rock slope had a design basis or were the bolts installed in the field without a design based approach. Again, by the end of the day, the 1975 design report for the Powerhouse and Vapor Recovery slope was provided. This report would have been valuable at the outset of the study in summer 2006, but its existence was unknown to Dr. West prior to today's meeting. Golder and Alyeska personnel stated that following the failure of the Power-Vapor Recovery Slope during construction, a design for the failed slope was obtained. This same design was used subsequently for the other slopes on the site as well.

Dr. West also asked for information on bolt spacing. No as-built drawings exist that show the position of the bolts. Additional bolts have been added from time to time. Drain hole locations are not documented either. A request was made for the onsite seismograph readings that coincide with major earthquake shaking in the Anchorage-Valdez area. Jim Roddick is to supply this information to Dr. West.

Graeme Major and Terry West discussed the pore pressure situation and whether the fractures in the slope were through-going or not. This aspect will be further considered in a subsequent report submitted by Dr. West

After lunch we toured the VMT site. Barry Roberts drove one Alyeska vehicle with Terry West and Tom Kuckertz riding along. Rhonda Williams drove the other Alyeska vehicle with Bucky Tart, Graeme Major and Greg Kinney included. We stopped at these sites: 1) Ballast Water, 2) Power Vapor and 3) West Fire Water slope (West Manifold). Notes and photos were taken.

For the West Manifold area, a notch in the buttress allows water to flow out near a tank facility. Sediment marks well up on the structure were observed. Conclusion by the field party, this notch should be filled in to prevent continuing runoff from the bench area above.

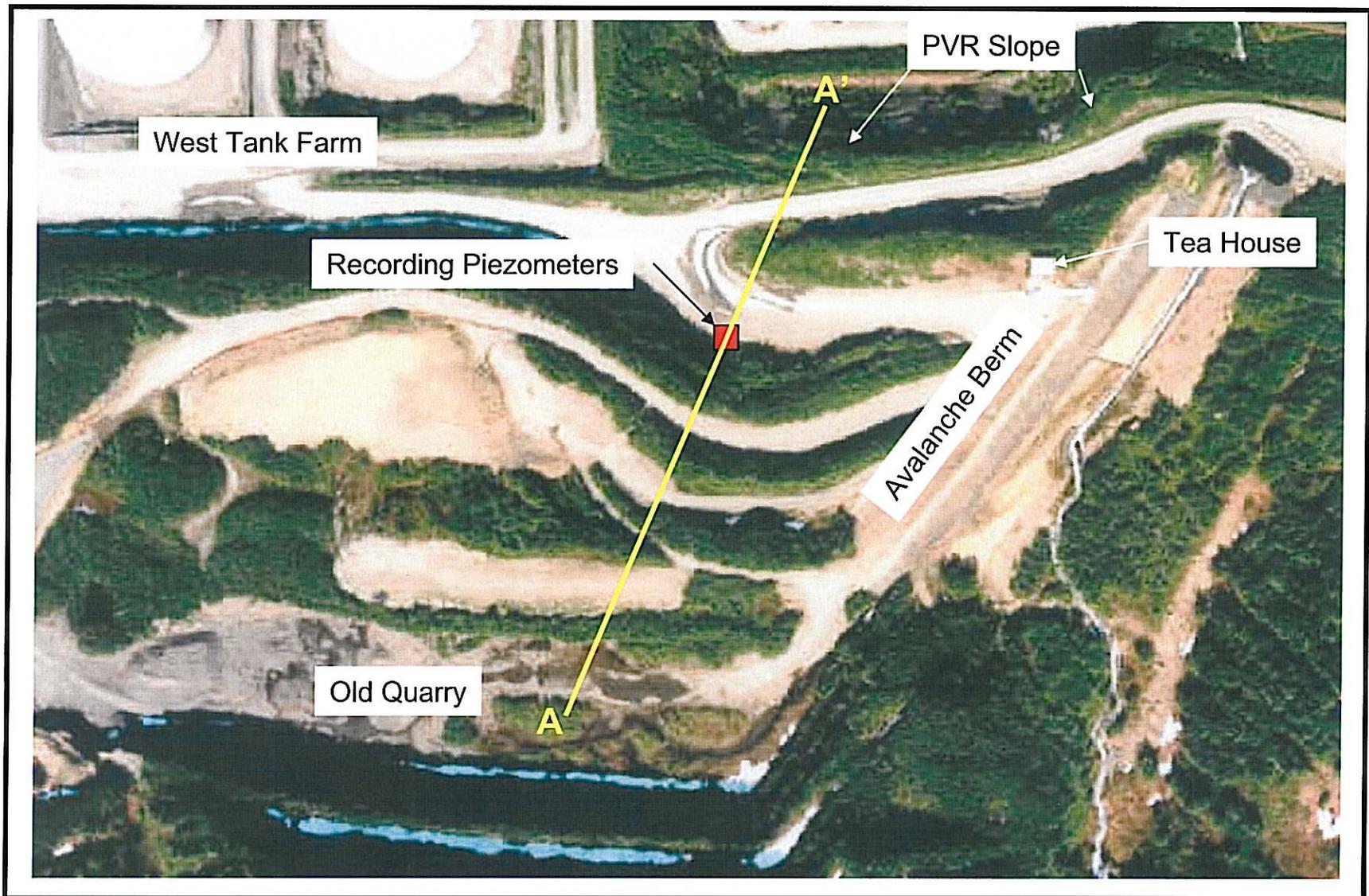
Back to the conference room. Terry West requested information on the extra piezometer installed in the dam area that corresponds to piezometer readings for other slopes. It was not determined if these data are available for public access. Subject still pending.

End of day and back to Valdez and to the motel for dinner and to sleep.

Valdez, July 16

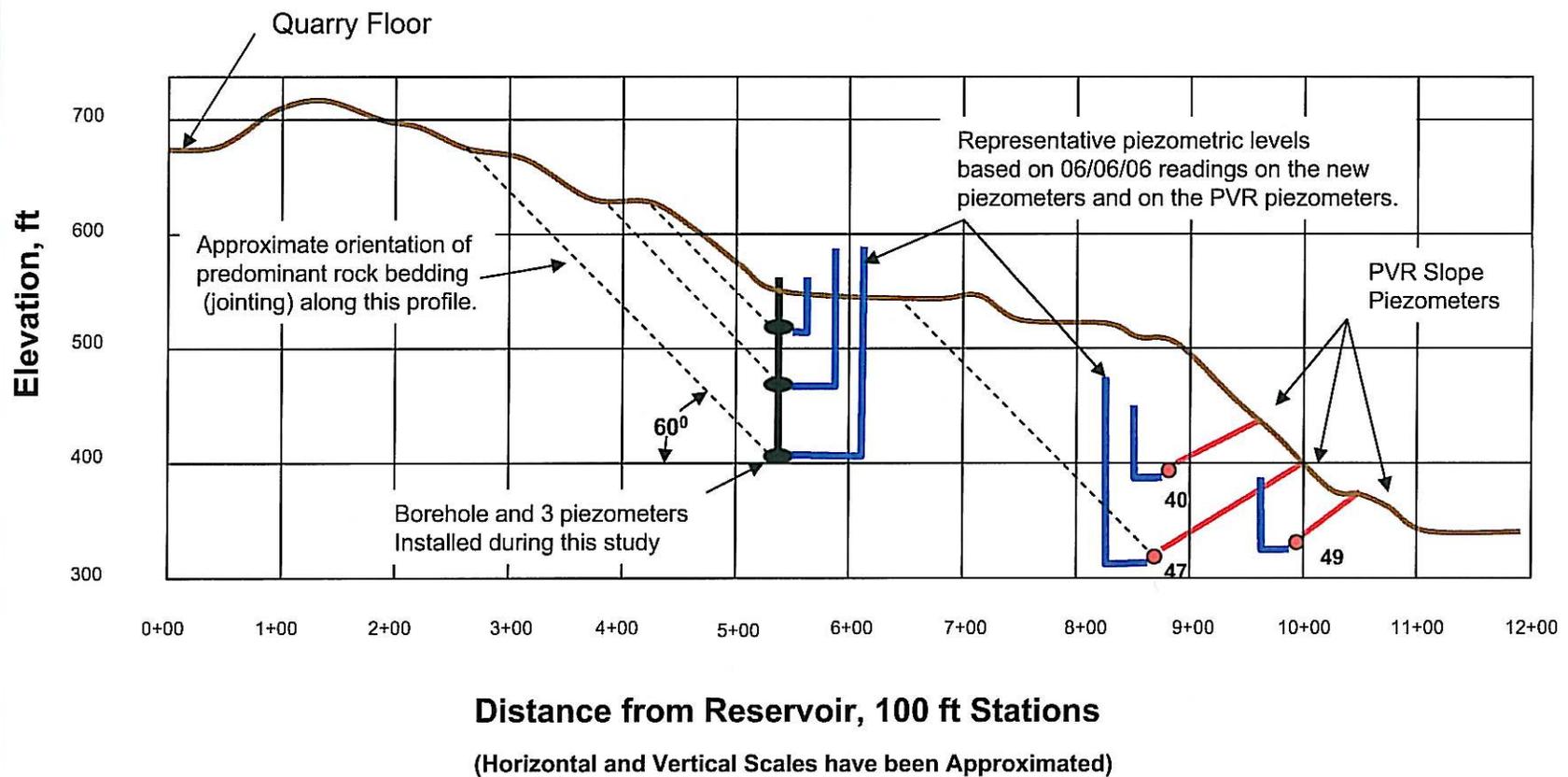
Dr. West viewed the more recent cut slopes in the area. The extensive rock cuts behind the Ferry Terminal were examined and photographed. Several joints and fractures show lengthy extensions of 1/2 the height of slope or more. He also viewed the rock cut on the road to the VMT site near the outlet for Solomon Gulch Dam, the outlet near the fish hatchery. This cut was examined and photographed. Several joints and fractures show lengthy extensions well across the steep slopes. Earlier in the day, Dr. West talked to Captain Stan Stevens during a boat cruise on Prince William Sound. Mr. Stevens was brought up to date regarding Dr. West's visit yesterday to VMT.

Appendix C. Figures 1-3 from Design Report, Proposed Dam Across the Rock Quarry, at VMT, by Golder and Associates, 2006(?)



Location of Recording  
Piezometers and Profile A-A'

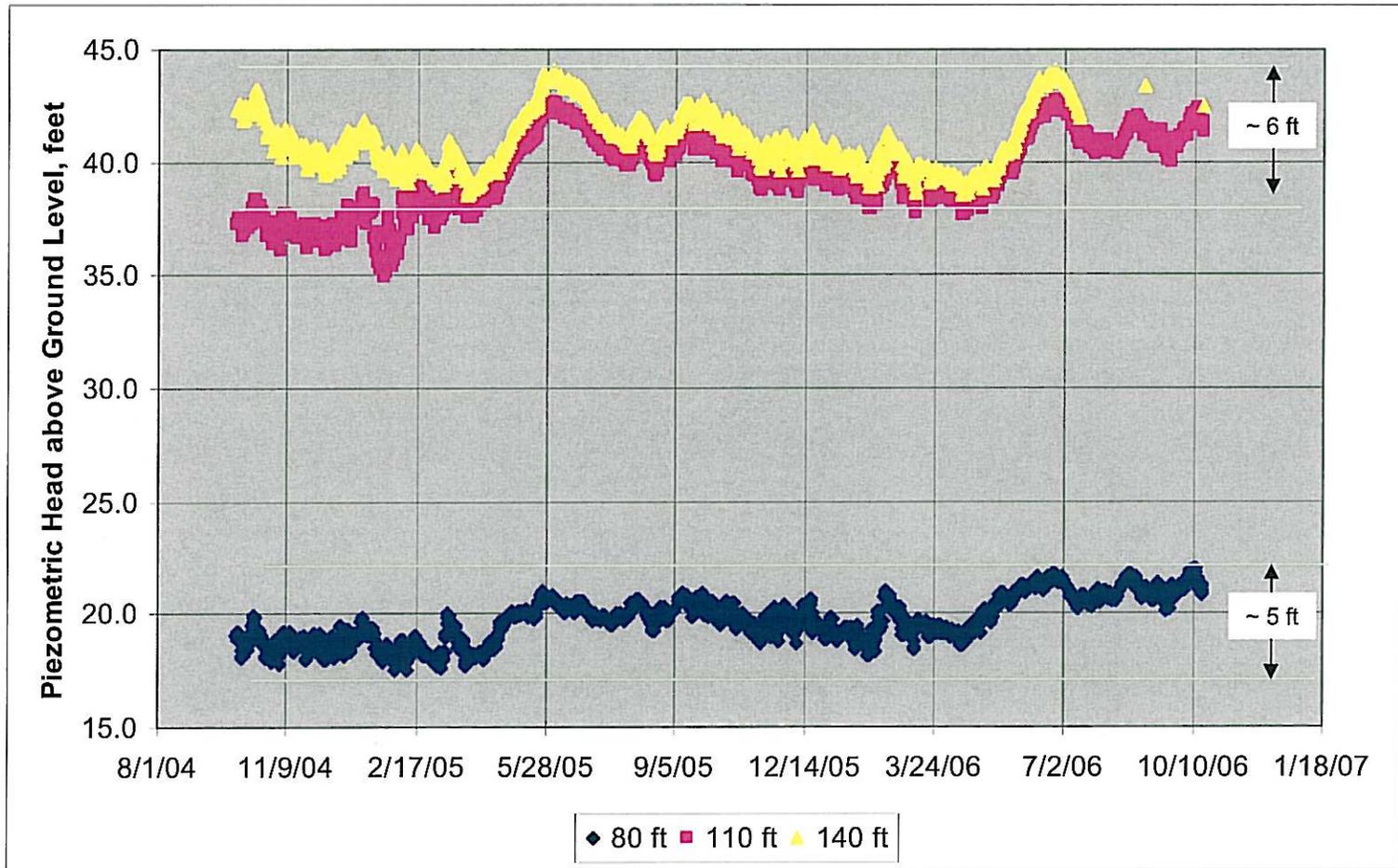
Figure 1



Approximate Profile A-A'  
Quarry to PVR Slope

Figure 2





Recording Piezometer Data  
from Aug 04 to Oct 06

Figure 3



Appendix D. Stability Analysis, PVR Slope, Factors from 1975 Design,  
Recalculated by West and Cho, 2008.

Example FS calculation sheet for Case 4

<Step 1> INPUT Data			
Dip of Failure Plane =	16.0	degree	Fault
Dip of Tension Crack =	50.0	degree	Foliation
Dip of Slope face =	48.0	degree	
Cohesion =	0.0	psf	FS=
Friction angle =	35.0	degree	<b>0.73</b>
Unit Weight of Rock =	160.0	pcf	
Unit Weight of Water =	62.4	pcf	
Height of Slope (H) =	125.0	ft	$H_w/H_{slope} = 0.80$
Block Width =	10.0	ft	

<Step 2> Selection of Pseudostatic Coefficient (ah)			
Horizontal Coefficient (kh) =	0.30		$a(kv/kh) = 0.0$
Vertical Coefficient (kv) =	0.00		

<Step 3> Calculation of weight of unstable block			
b =	323.4	ft	
L =	453.5	ft	
Block Thickness =	55.0	ft	
b' (b - block thickness) =	268.4	ft	
L' =	85.8	ft	(by trigometry)
TC1 (vertical) =	101.3	ft	
TC2 (inclined) =	132.3	ft	
Area =	453.5	ft	
W =	10,580,144.7	lb	(per 10' width)

<Step 4> Calculaiton of Pore pressure V			
Zw1 (vertical) =	76.0	ft	(no water Zw1=0) (fully saturated: Zw1=TC1)
Zw2 (inclined) =	99.2	ft	
V =	2,352,490.1	lb	(per 10' width)

<Step 5> Calculaiton of Pore pressure U  
U = 2,035,504.4 lb (per 10' width)

<Step 6> Add Support Force  
T = 1,200,000.0 lb (tensioned, active, per 10')  
Inclination 0.0 degree (from hor. upward)

<Step 7> Calculation FS  
Resisting Force = 6,014,515.2 lb  
Driving Force = 8,228,728.1 lb  
FS = **0.73**

Conditions	Pore Pressure ( $H_w/H_{slope}$ )	Earthquake ( $a_h$ )	FS
Current 1	0.8	0	1.28
Current 2	0.9	0	1.03
Dry 1	0	0	2.92
Dry 2	0	0.3	1.52
Dry 3	0	0.6	0.81
Saturated 1	1	0	0.84
Saturated 2	1	0.3	0.52
Critical 1	0.8	0.15	0.94
Critical 2	0.8	0.3	0.73

Appendix E. Photographs, Fresh Rock Cuts, Valdez Area, Showing Extensive Fracture Surfaces.



ACCESS ROAD TO VMT

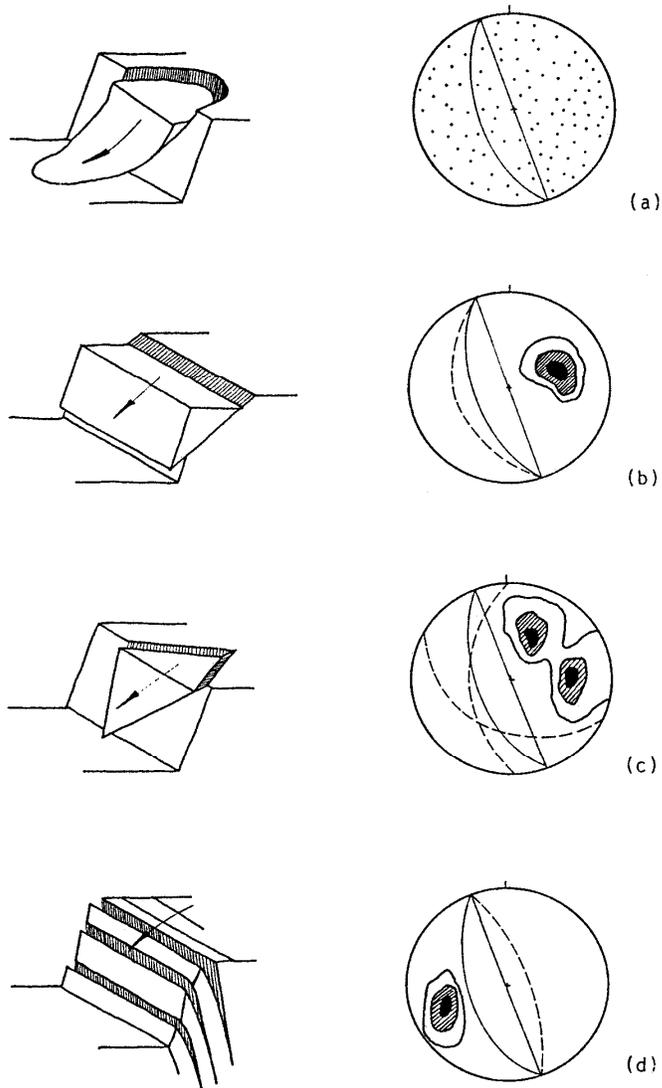
ONE LANE  
ROAD

ONE WAY

FERRY TERMINAL, VALDEZ

Appendix F. Four Types of Rock Slope Failures, from report by West and Cho,  
2007.

Figure 7.1 Four types of rock slope failures (After Hoek and Bray, 1981)



(a) Circular Failure (b) Planar Failure (c) Wedge Failure (d) Toppling