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Seismic interpretation of Hilat-Al-Sad landslide, Muscat, Sultanate of Oman

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Abstract

Recent landslides of Pakistan (2005), Boulivia and Indonesia (April, 2003) caused huge losses of lives and property. Such threatening landslides are widely distributed in the world and in Oman too. Several have occurred in the last two decades due to slope failure and/or rock cutting for socio-economic purposes. Hilat Al-Sad landslide is one example of Al-Wattayah(Muscat) landslides which spread panic in 1996. It was activated just after the completion of a rock cut. The sliding raised a question whether it happened due to rock cutting activity or due to regional stresses.

For searching the evidence, shallow seismic refraction investigations were carried out in this structurally folded and faulted rocks of varied lithology and ages, using 24-channels seismic recorder and the hammer as energy source. The orthogonal seismic spreads revealed the existence of two perpendicular faults within 20 meters depth. But sliding was found to be unrelated to the faults; it appears to have occurred due to toe failure on a weaker plane developed recently or previously.

Keywords: Landslides; geophysical applications; seismic interpretation

1. Introduction

Hilat Al-Sad landslide is located (GPS UTM: 2610155 N, 0655701 E) in Al-Wattayah area of Muscat region. This landslide was activated in 1996 and brought down a huge mass of rock and soil (about 100,000 cubic meters) to the ground. This happened just after the completion of a rock cut made for the extension of a business outlet.

The head of the failed slope of the landslide (as shown in photograph-A) is located at the contact between marly limestone of Jafnayn Formation (Tertiary) and the schist/siltstone (top layer) of Muti Formation (Cretaceous), while the toe of the slide lies in gray-green weathered clayey limestone (Al-Sinnai et al., 2000).

The drainage ditch and the retaining wall built after the mishap to contain and prevent the landslide was cracked and bulged out after some due to stabilizing stresses. The cracks are visible in photograph-B of Fig. 1.

2. Landslides

Landslide by definition is a downward and outward movement of slope forming rock material. The slide on surfaces involves failure of the earth materials under shear stress, and is influenced by several factors, such as geology, slope geometry, pore pressures, erosion, surcharge, human activity or the earthquakes. It occurs along one or several surfaces that are exposed or predictable. These surfaces may be planar, non-planar, steep, gentle, concave upward, regional, local, site specific, pre-existing or the fresh (Jones, 1973). The failure of a rock often is related to instability of slope which is definitely higher in extensively jointed and faulted areas. Slides can also be triggered by earthquakes globally (for example, in Pakistan in 2005) which cause an increase in shear stress and a decrease in shear strength of rocks. Because the ground motion during earthquakes involves the slopes to repeated loading and induces cyclic stresses in the soil and produces irreversible changes in pore pressure giving consequently the long term and short term changes in the soil strength (Arango and Seed, 1974). Landslides generally occur when slope stability becomes unstable due to natural causes or human activities (Morgenstern and Price, 1965); the human activity appears to be the cause of Hilat Al-Sad landslide.

Al-Wattayah actually is a part of the Saih Hatat geological unit (Fig. 2) which forms broadly a major domal structure, exposes Pre-Permian to Tertiary main tectono-stratigraphic sequence of the Oman Mountains, and reveals structural complex of overprinting in several phases of tectonism.

The studied area shows a contact between Tertiary rocks of marly limestone and schist/siltstone of Cretaceous age. The rocks are heavily deformed by folding, faulting (thrust, normal, and strike slip) and fracturing, and the lithostructural complexity is a consequence of the north-south, east-west trending structures resulted in episodes of compressional and extensional deformations in different ages (Hanna, 1990).

Fig. 1. A: general view of the landslide.

Fig. 1. B: heaving effect in the retaining wall at the toe of the slope.

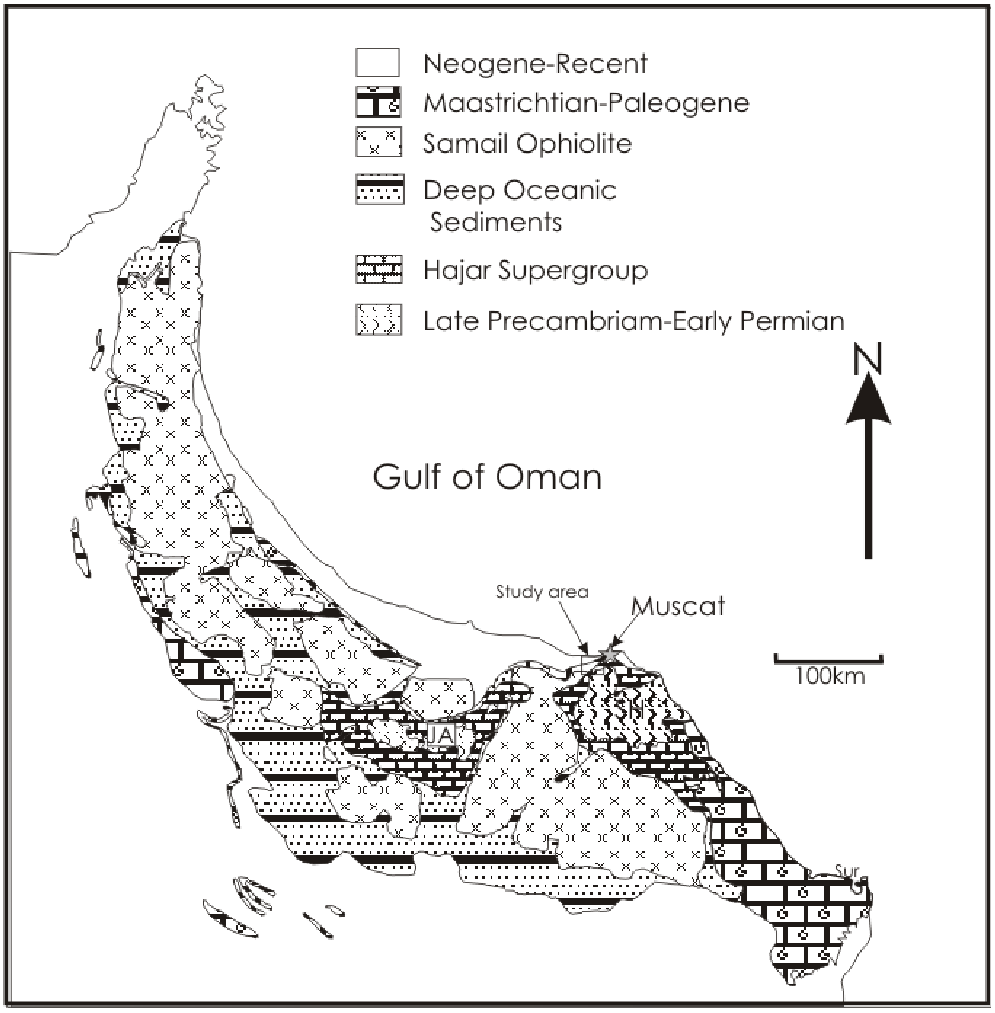

Fig. 2. Geological map of the study area and its surroundings.

Since folded-faulted zones are prone to sliding, the Hilat-Al-Sad landslide that occurred after a rock cutting activity raised a question whether sliding triggered due to fault activation or due to toe failure of the rock. To address this question a seismic refraction survey was planned, and conducted in a small open space in front of the sliding plane. The idea was to image shallow geological features buried under the recent overburden and correlate them with the sliding plane.

3. Seismic Field Geometry

For the earlier mentioned objective the seismic refraction survey was conducted with 24-channels seismic set, and the data was acquired along two lines oriented parallel (east-west) and perpendicular (north-south) to the rock face. The seismic field geometry, equipments and the acquisition parameters used in this survey are given in the Table 1.

Table 1. Field parameters of the study area.

Energy source	Hammer (6 kg)
Shooting pattern	Reverse shooting (end, far-end & central)
Minimum offset	2.5 & 5 meters
Maximum offset	120 meters
Geophone interval	5 meters
Geophone per channel	1
Recorder	24 channels
Record length	128 ms
Sample interval	125 microsecond
Stacking	6-10
Gain	Fixed/variable
Locut/Hicut filter	35 Hz, 500 Hz

The line parallel to the rock face (east-west) comprises two seismic spreads with an overlap of five geophones. Each seismic spread was shot from ends, far-ends, and the center, using 6 kg hammer as the energy source. Much care was taken in planting and connecting geophones, striking the hammer, stacking, producing seismic records, and in picking the first arrivals. Vertical stacking (Ali et al., 1990) helped substantially in the improvement of data quality. One field file is presented in Fig. 3 to demonstrate the quality of first arrivals which can be picked with certainty of 0.5 msec. The visible background noise on far channels has not affected much the first arrivals.

4. Seismic Interpretation

As regards interpretation of seismic refraction data, several methods based on delay time(Wyrobek, 1956; Gardner, 1967; Bary, 1967 and Palmer, 1980,1991) and wave construction technique (Thornburgh, 1930;Hill, 1987;Vidale, 1990; and Aldridge and Oldenburg, 1992) are available in literature, however, Hagedoorn's plus-minus method and Palmer's GRM technique are the ones which are commonly used. The delay time concept provides opportunity to interpret first arrival data into planar/non-planar interfaces, whereas wave construction technique extended to ray tracing (Cerveny and Ravindra, 1971; Cerveny et al., 1974) addresses complex subsurface structures that are difficult to handle analytically. It is important to mention that a layered sequence of planar refractors gives rise to a travel-time graph consisting of a series of straight-line segments, whereas irregular travel-time curves indicate the situation of non-planar refractors, or alternatively the lateral velocity variations within individual layers. The reliability of interpretation depends upon velocity function because velocity inversion, hidden layers, and inappropriate velocity contrasts effect severely the results.

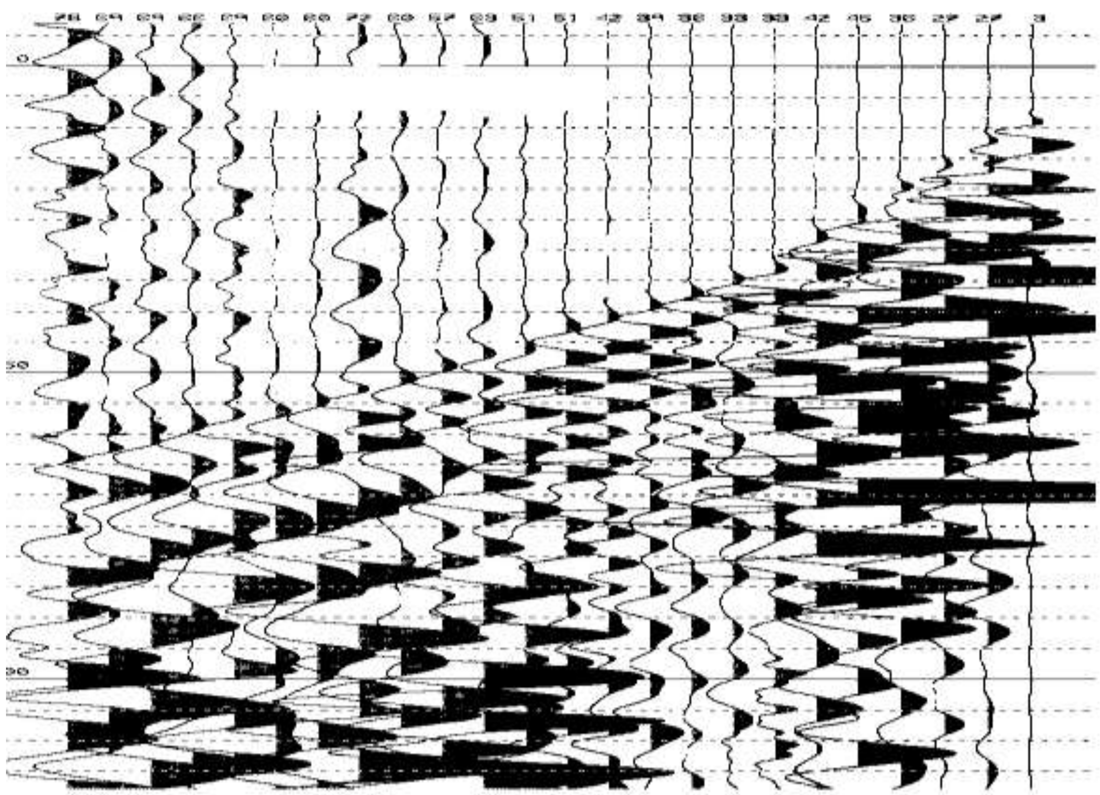

Fig. 3. Seismic record of an end shot.

5. Seismic Modeling and discussion

The P-waves first arrival data collected from 6 shots of two seismic spreads along the line parallel to the slide plane is presented compositely on one T-X graph shown in Fig. 4. The computer modeling done with iterative ray tracing scheme and with the assumptions of three layered geological set up, reveals subsurface geology that is shown in Fig. 4. The seismic velocities of 1st, 2nd, and 3rd layer respectively are 420 m/s, 2620 m/s, and 4850 m/s. The shape of the 2nd refractor or the upper surface of the 3rd layer exposes a step like function which can be interpreted as a steep normal fault (marked on the figure) that runs perpendicular to the face of the rock. It strikes almost north-south and dips towards east. The right-sided eastern down thrown block appears to be displaced by 15 to 20 meters along this fault. The upward projection of the fault through 2nd layer (as shown in 2-layers modeling case, Fig. 4, bottom) gives its surface trace near geophone location 21. The eastern block comprising schist/siltstone is serving as the hanging wall (down thrown) against the western limestone block. This fault plane is orthogonal to the slide face, hence has no relation with sliding plane.

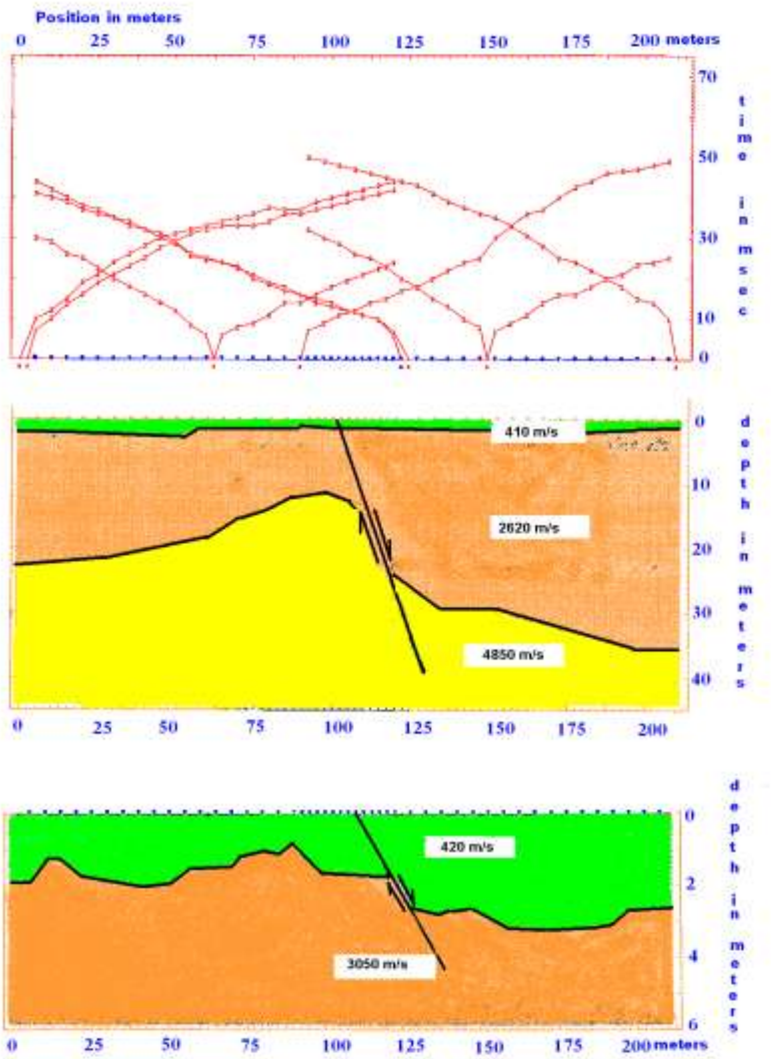

Fig. 4. Top: Composite T-X graph of seismic spreads A &B, parallel to the slide face.
Middle: Seismic interpretation of T-X data assuming 3-layers case.
Bottom: Seismic interpretation of T-X data assuming 2-layers case.

The seismic line shot perpendicular to the rock face was also modeled identically with 3-layers assumption (Fig. 5). The seismic velocities for 1st, 2nd, and 3rd layers respectively are 422 m/s, 2700 m/s, and 4970 m/s. The seismic interfaces separating the layers are non-planner in nature, and the geometry of second interface (or upper surface of the 3rd layer) reveals again the probability of a normal fault located 40 meters away from the sliding rock. The fault seemingly trends ENE-WSW, and dips southwards (road side) at an angle of 12 degrees (Figs. 5b & 5c). The displacement on the fault is roughly 8 meters.

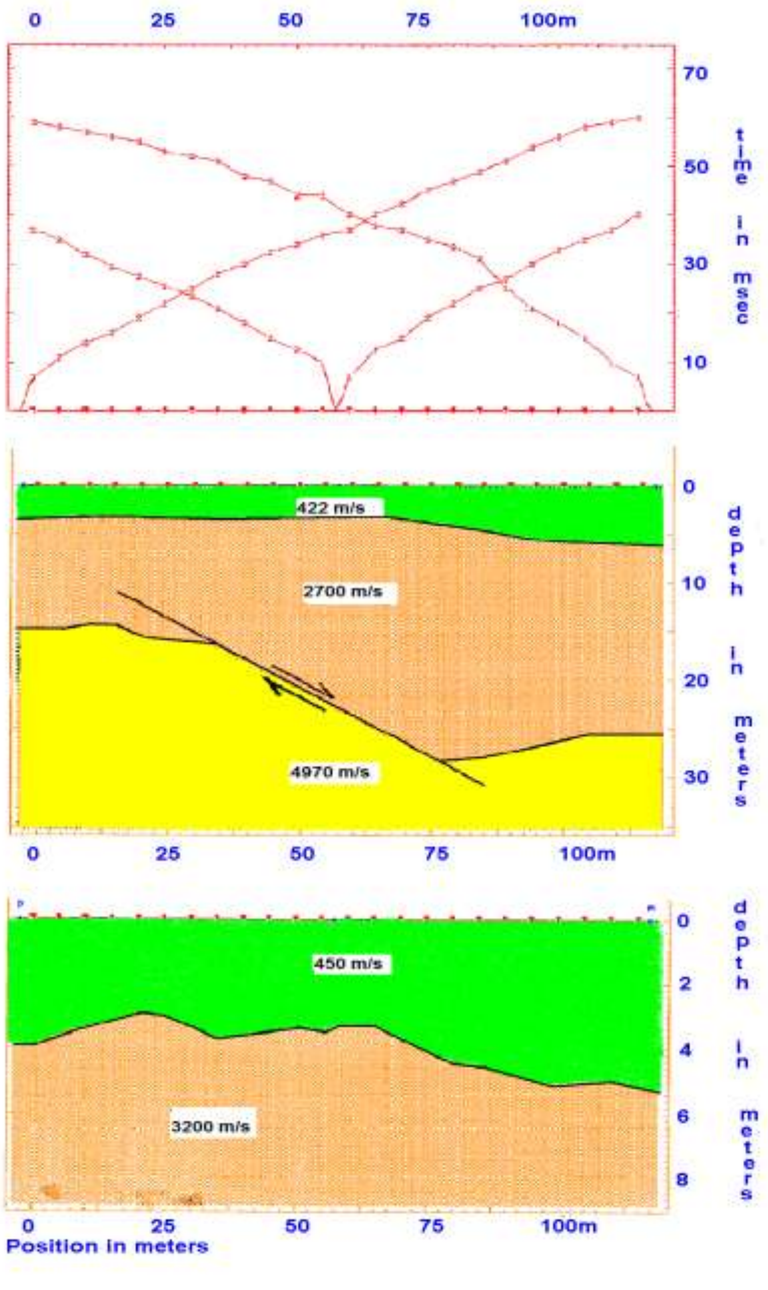

Fig. 5. Top: T-X graph of seismic spread perpendicular to the rock face.
Middle: Seismic interpretation of first arrival data in 3-layers assumption
Bottom: Seismic interpretation of first arrival data in 2-layers assumption.

This fault is of consideration because it runs parallel to the face of the slide. The more interesting feature of the fault is; the hanging block (towards the road) carries main business outlets such as the Petrol station, Car show rooms and other business ventures. Now the question is, whether this fault is related to sliding or has contributed in triggering the landslide? For that purpose the fault plane was projected upwards linearly and it crossed in air the slide face obliquely. If the fault is supposed to be of listric type then the upwards projection of the fault plane may be connected with the present sliding plane or with any of the fracture planes running down into the rock parallel but behind the sliding plane. This assumption apparently sounds appropriate to create a link or correlation with the sliding plane, and furtherance to the tectonic forces.

But this is an assumption, not a reality, because the fault is roughly 15 to 25 meters deep, and 40 meters away in the plain area in front of the sliding rock face. If the fault is activated by tectonic activity, it would have generated a strong earthquake causing not only a small slide but a heavy and far spreading destruction. That did not happen, there is no such report. Even no cracks are observed in the nearby commercial buildings. This means the possibility of activation of the fault is negligible. The mentioned landslide therefore is a localized phenomenon.It appears that the triggering force required for land sliding is generated by toe failure of the weaker rock after the rock cutting activity. Cheema et al. (2002) suggest on the basis of joint shear strength data and stereonet analyses that the presence of weak rocks such as claystone, mudstone, shale and siltstone poses slope stability problems because of their low cohesion and the development of tension cracks at the crest of the slopes. It may be possible that some sort of fracture or the listric fault as a splay of the main fault might have existed earlier, and the present failure plane formed under shear stress due to toe failure overlapped coincidently and facilitated sliding activity. This has nothing to do with the fault movement. Further, this occurrence does not mean that final stability condition is reached in short time, it takes time and is apparent from the development of bulge and cracks on post-built retaining wall. In such situations it is precautionary to check the presence of cracks on the crown of the slide, because their presence gives indication of future rock instability.

6. Conclusions

Though several reasons cause land sliding (Watkins and Hughes, 1993), the seismic study at Hilat Al-Sad landslide reveals shallow perpendicular faults but suggests no relationship with tectonic reasons. Predominantly it is concerned with toe failure due to rock cutting activity. In such probabilities there is a need of prior consideration of safety factor which addresses the mechanisms to recondition the slope in an acceptable limiting equilibrium along the slide surface.

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References

Aldridge, D.F., Oldenburg, D.W., 1992. Refractor imaging using an automated wave front reconstruction method. Geophysics, 57, 3, 378-385.

Ali, M., Miller, R.D. Steeples, D.W. 1991. Shallow faults mapped with seismic reflections: Lost River Fault Idaho. Geophysical Research Letters. 18(9), 1767-1770.

Al-Sinani, Y., Al-Hosni, T. Cheema, T. 2000. Investigating landslide hazards in Muscat Area, Sultanate of Oman. Proc. 1st International conf. on Geotechnical, Geoenvironmental Engineering Management in Arid Lands, 209-216.

Arango, I, and Seed, H.B., 1974. Seismic stability and deformation of clay slopes. Journal of Soil Mechanics and Foundation division, American Society of Civil Engineers. 100(GT2), 139-156.

Barry, K.M., 1967. Delay time and its application to refraction profile interpretation. In: Musgrove, A.W. (Ed.), Seismic Refraction Prospecting. Society of Exploration Geophysists, Tulsa, 348-352.

Cerveny, V., Ravindra, R., 1971. Theory of seismic Head waves. University of Toronto Press.
Cerveny, V., Langer, J., Psencik, I., 1974. Computation of geometric spreading of seismic body waves in laterally Inhomogeneous media with curved interfaces. Geophy. Journal of the Royal Astronomical Society, 38,9-20.
Cheema, T., Al Harthy, A., Al Sinnai, Y., Al Hosni, T., Al Aghbari, M., 2002. Landsliding associated with the urban development in the Muscat Area, Sultanate of Oman. American Geophysical Union, Spring Meeting Abstract, H51A-01.
Gardner, L.W., 1967. Refraction seismograph profile interpretation. In: Musgrove, A.W. (ed.), Seismic Refraction Prospecting. Society of Exploration Geophysicists, Tulsa, 338-347.
Hanna, S.S., 1990. The Alpine deformation of Central Oman mountains. Geological Society of London (Special Publication), 49, 341-348.
Hill, N.R., 1987. Downward continuation of refracted arrivals to determine shallow structure. Geophysics, 52 (9), 1188-1198.
Jones, F.O., 1973. Landslides of Rio de Janeiro and the Serra das Araras escarpment, Brazil. United States Geological Survey, Professional paper, 697, 42.
Morgenstern, N.R., Price, V.E., 1965. The analysis of the stability of general slip surfaces. Geotechnique, 15 (1), 79-93.
Palmer, D., 1980. The generalized reciprocal method of seismic refraction interpretation. Society of Exploration Geophysicists, Tulsa.
Palmer, D., 1991. The resolution of narrow low velocity zones with the generalized reciprocal method. Geophysical Prospecting, 39 (8), 1031-60.
Thornburgh, H.R., 1930. Wavefront diagrams in seismic interpretation. Bulletin American Association of Petroleum Geologists, 14,185-200.
Vidale, J., 1990. Finite difference calculation of travel times in three-dimensions. Geophysics, 55(6), 521-526.
Watkins, A., Hughes, S., 1993. Module 4, Landslides, slope failure, and mass wasting processes. Environmental Geology, 306/506.
Wyrobek, S.M., 1956. Application of delay and intercept times in the interpretation of multi-layer refraction time-distance curves. Geophysical Prospecting, 4(2), 112-130.