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# CASE STUDIES OF LANDSLIDE HAZARD OCCURRENCES IN GEOTHERMAL FIELDS: THE PNOC-EDC EXPERIENCE

R. D. Leynes, W. P. C. Pioquinto and J. A. Caranto

PNOC Energy Development Corporation, Merritt Road, Fort Bonifacio, Metro Manila 1201, Philippines

## ABSTRACT

***Two case studies are presented to demonstrate landslide hazard assessment in the PNOC-EDC geothermal fields. The first is in the Leyte Geothermal Production Field (LGPF) and the second is in the Mindanao Geothennal Production Field (MGPF). Using simple yet reliable field criteria to assess slope instability, low to high slope failure potentials of specific sites are qualitatively assessed.***

***Based on the risk classification timely installation of effective engineering measures are implemented. This is demonstrated in the case of the MGPF hazard assessment where the timely installation of pipe shelters shielded pipelines from frequent landslides and thus avert costly damage. Follow-up monitoring using improvised and locally fabricated tools in selected high-risk areas are implemented in selected sites to monitor, if any, future landslide and ground movements. This is shown in the case of Tower No. 7 in LGPF.***

## 1.0 INTRODUCTION

Surface development.of a geothermal project requires extensive civil and other anthropogenic activities. From the exploration drilling stage up to exploitation stage when the power plant is operational, the natural topography will be re-configured owing to the various infrastructures that will be constructed. Minor to moderate changes in the natural slope geometry will ensue following the construction of roads, pads, pipeline routes, marshalling stations, power plant location, and fluid collection and disposal system (FCDS) among others. Depending on the project site location, existing land plant cover is similarly affected. These modifications to the natural slope condition and, land cover of an area could bring about slope instability which may eventually lead to landslides in the absence of slope instability mitigating measures. The consequences of these landslides vary depending on the severity of the damage to infrastructures. Another major consequence of landslides is lost revenue, which happens when major facilities like roads, well pads, wells and pipelines are damaged. Thus, coping with landslides has been one of the major concerns of PNOC-EDC.

This paper aims to discuss the common landslide hazard studies and occurrences within PNOC-EDC geothermal fields - the methods of assessment, the possible causes, the engineering mitigation applied, and the monitoring techniques employed among others. Two PNOC-EDC geothermal fields will be cited as examples wherein landslide hazard studies were conducted.

### 1.1 Overview of the Leyte Geothermal Production Field (LGPF) and the Mindanao Geothermal Production Field (MGPF)

LGPF is situated at the north-central portion of Leyte Island (Fig. 1). The field is located within the bifurcating branches of the Philippine Fault, an active left-lateral strike-slip fault traversing the whole of Leyte and the Philippine archipelago. The Philippine Fault and related faults and fractures provide major permeability to the wells drilled in the area. The rock sequences within the geothermal field are mostly fresh to slightly weathered andesite to dacite lavas. Subsurface hydrothermal alteration generally increases with depth. At depth, about 1500 m below mean sea level, breccia/conglomerate with fragments of altered microdiorite, quartz monzodiorite, and minor volcanics set in a fine-grained arenaceous to argillaceous groundmass, and minor intercalations of sandstone, siltstone and claystone named Mahiao Sedimentary Complex (MSC) constitute the sedimentary sequence of the field (Delfin, et al., 1995).

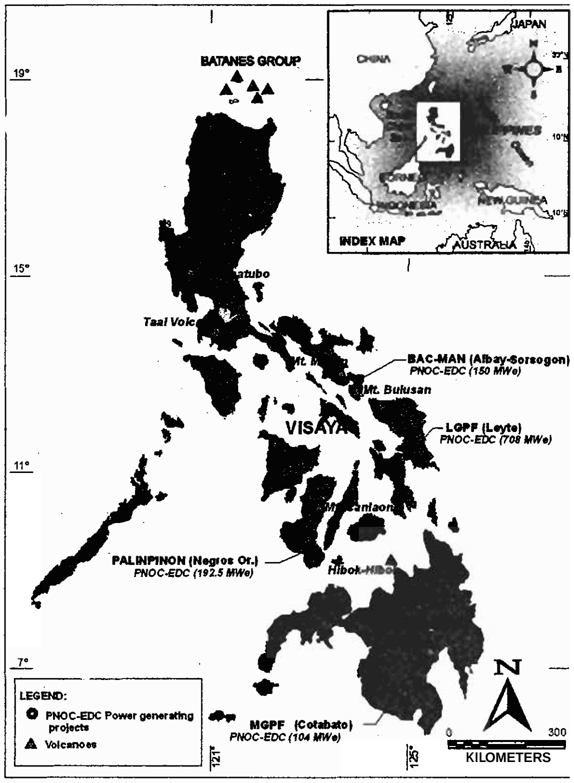


**Figure 1.** Location map of Leyte Geothermal Production Field (LGPF) and Mindanao Geothermal Production Field (MGPF).

The field is subdivided into seven sectors namely: 1) Upper Mahiao, 2) Mahiao, 3) Sambaloran, 4) South Sambaloran, 5) Malitbog, 6) Mamban, and 7) Mahanagdong. These sectors host a total of seven power plants with a combined power generating capacity of 708 MWe including the optimization plants (Herras, et al., 1998).

On the other hand, the Mindanao Geothermal Production Field (MGPF), with an area of about 30 $km^2$, is located on the northwest flanks of Mt. Apo, in southwest Mindanao (Fig. 1). The surface geology of MGPF is dominated by rocks of belonging to the Apo Volcanics (AV) (Sambrano, 1998). The younger AV found east and south of the Mt. Apo summit are mostly andesitic domes and lavas. The older AV are distributed mainly to the northwest and western side of Mt. Apo. Structurally, the geothermal field is cross-cut by a dominant northwest-southeast trending fault system, and a collapse feature known as Sandawa Collapse (Sambrano, 1998).

Two power plants, situated in two sectors named MIGP and M2GP are operational in MGPF. The two power plants produce a combined power output of 104 MWe (52 MWe for each plant).

## 2.0 CRITERIA AND FIELD TECHNIQUES

In PNOC-EDC projects, the landslide hazard evaluation is carried-out using the criteria adapted from Lee and Huang (1992). The technique considers geology, general slope condition, environment and hydrogeology, which are the factors that control the slope stability. Each primary factor is given secondary level factors with an assigned qualitative weight (Table 1). Based on these factors, a set of criteria is established to determine the qualitative degree of instability of an area (Tables 2-5). The failure potential ranking of a specific area is qualitatively classified by summing up the assigned ratings (A, B, C, D, E) for each secondary level factors. This is further evaluated against the primary factors. The slope instability ranking is given in Table 6.

The evaluation is supplemented by the use of aerial photographs to determine geomorphological, and general geological characteristics of an area. The Rock Mass Strength Rating (RMR) technique is employed for assessment of rock failure potential. Measurements of joints and or microfaults, and creation of rose diagrams and stereoplots are also used in assessing slope instability.

## 3.0 ENGINEERING MEASURES AND MONITORING TECHNIQUES

Dealing with landslide hazards in PNOC-EDC geothermal fields can be grouped into four main categories, namely: 1) acceptance, 2) avoidance, 3) protection/prevention, and 4) remediation (Pioquinto, 1999).

### 3.1 Acceptance

As the name implies, this is accepting the fact that landslide is due to occur and man-made intervention is inapplicable and the course of action is to deal with the effect after the event has occurred. A common practice is to remove the landslide debris along roads and pads after each landslide occurrence. In the long run, this

Table 1. Factors adopted for slope instability

| Primary Level factor | Weight | Secondary level factor | . Weight |
|---|---|---|---|
| A. General Slope Condition | EI' | A1. Slope gradient/inclination | EI |
| | | A2. Slope height | EI |
| | | A3. Slope direction | I |
| | | A4. Deformation intensity | I |
| | | A5. Age of deformation | I |
| | | A6. Activity of deformation | EI |
| | | A7. Type of slope material | VI |
| 8. Geology | VI | 61. Rock type | VI |
| | | 62. Weathering grade | VI |
| | | 63. Orientation of discontinuity | VI |
| | | 84. Spacing of discontinuity | EI |
| | | 65. Rock mass | VI |
| | | 66. Presence/condition of faulting | VI |
| | | 87. Presence of altered grounds | VI |
| C. Environment | EI | C1. Type of vegetation | I |
| | | C2. Density of vegetation | VI |
| | | C3. Type of land use | EI |
| | | C4. Type of protection facility | VI |
| | | C5. Drainage facility | EI |
| D. Hydrogeology | EI | D1. Seepage | EI |
| | | D2. Permeability of top soils | I |
| | | D3. Presence of water course | VI |

*EI- Extremely important, VI- Very important, I- Impor

| Secondary level Factor under slope condition | Criteria for Evaluating Slopes | | | | |
|---|---|---|---|---|---|
| | A* | B | C | D | E |
| A1. Slope gradient (°) | 40-60 | 30-40/60-70 | >70 | 20-30 | <20 |
| A2. Slope height | >20 | 5-20 | | 2-5 | 0-2 |
| A3. Slope direction | Towards (area concerned) | Oblique | Parallel | | Opposite |
| A4. Deformation intensity | great | Unimpressive | Unclear | | Insignificant/ none |
| A5. Age of deformation | recent | Fossil | | | |
| A6. Activity of deformation | active | dormant | stabilized | Removed/ buried | None/ insignificant |
| A7. Type of slope material | Landslide material/ uricompactedfills | Clayey earths or weak semi-solid rocks | - | Semi-solid rocks | Solid rocks |

Table 3. Criteria for assessin

| Secondary level Factor under geology | | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| 61. Rock type | Unconsolidated pyroclastics | Laharic mat'ls | - | Volcanic breccias | Lavas |
| B2. Weathering grade | Completely weathered or residual soil | Highly weathered | Moderately weathered | Slightly weathered | Fresh |
| 63. Discontinuity orientation | e-w or parallel to concerned area & dipping towards | Oblique and dipping towards | perpendicular | Dipping opposite | |
| B4. Discontinuity spacing (cm) | <6 | 6-20 | 20-60 | 60-200 | >200 |
| B5. Rock mass | crushed | irregular | Columnar/tabular | blocky | Massive |
| 66. Presence/condition of faulting | Active, <50m from concerned area | Active, >50m | Inactive, <50m | Inactive, >50m | None |
| B7. Presence of clay and or acid-altered grounds | Predominantly clay-altered | Moderately clay altered | Slightly clay altered | - | None |

*A - Very high, B - High, C - Med

| Secondary level Factor under environment | | Criteria for Evaluating Slopes | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| C1. Type of vegetation | No cover | grass | Grass > trees | - | |
| C2. Density of vegetation | Very low (<10%) | Low (10-25%) | Medium (25-50%) | High (50-75%) | Very high (>75%) |
| C3. Type of land use | Pipeline/FCDS, pads | road | | | |
| C4. Type of protection facility | none | benching | Rubble masonry | | |
| C5. Drainage facility | none | | Interceptor canal | | |

| Secondary level Factor under hydrogeology | Criteria for Evaluating Slopes | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| D1. Seepage | Continuous flow | Occasional drops | Always damp | - | Dry |
| D2. Permeability of top soils | Low (clay) | Medium (silt) | High (sand) | | |

*A - Very high, B - High, C - Medium, D - Low, E - Very low

| Ranking | Explanation |
|---|---|
| VERY HIGH INSTABILITY | ratings of A with EI +VI weights are dominant |
| HIGH | ratings of A with I weights + B with EI +VI weights are dominant |
| MEDIUM | ratings of B with I weights + C with EI + VI weights are dominant |
| LOW | ratings of C with I weights + D with EI + VI weights are dominant |
| VERY LOW | ratings of D with I weights + E with EI + VI weights are dominant |

practice typically burdens the company as a result of additional maintenance costs arising from road and pad repair, FCDS cut-out and plant shutdown.

### 3.2 Avoidance

This is usually undertaken during the early stages (e.g. planning stages) of a project. In this strategy, areas assessed to be very high to high risk are avoided during actual construction of facilities and road network.

### *3.3* Protection/Prevention

The objective of this scheme is to limit the potential for slope failure rather than repairing the damage after the Occurrence of the problem. The very essence of this scheme is good land management. Re-vegetation of bare slopes and opened-up areas together with other soil conservation measures help in minimizing soil erosion, and siltation of waterways. Construction of masonry wall or pipe shelters in areas assessed to be undergoing slope movement is also a way of slope protection and landslide prevention.

### 3.4 Remediation

Remediation measures are aimed at stopping or mitigating the destabilizing process using engineering measures. Remediation measures can be further classified into: ***1) changing the geometry*** of ***the slope, 2) control of surface water*** and ***seepage, 3) rigid structural barriers, 4) flexible support structures, and 5) vegetation.***

Except for the flexible support structures, the abovementioned remediation measures have been used in PNOC-EDC geothermal fields. The first remediation technique was employed in LGPF at the former Mahiao quarry area. In this area, the downward movement is occurring due to the removal of the toe support due to quarrying. Thus, the load above was reduced and the slope was benched to prevent further slippage. Photo I shows the removal of upper load along the slope of the quarry face. The second scheme, control of surface water and seepage, was applied in the Malitbog quarry area where concrete water cascades were constructed water saturation of the formation. The more common remediation technique employed at PNOC-EDC is the construction of rigid structural barriers such as rubble masonry wall, concrete masonry wall, concrete lined canals, and pipe shelters. Photos **2-3** show examples of these structural barriers. Vegetation is also similarly included in this classification as a means of remediation. Vegetation is selectively conducted in the landslide affected area.

## 4.0 MONITORING TECHNIQUES

After the engineering mitigating measures are implemented, the most critical sites need further monitoring to determine whether the installed remedial measure is successful in preventing landslides. In the past, landslide monitoring in PNOC-EDC is carried-out through Electronic Distance Measurements (EDM) using a Geodimeter total station meter. This is done by regularly conducting measurements over pre-established benchmarks, which are strategically located in stable (reference point) and creeping (monitoring stations) grounds. Distances between the reference and monitoring stations are measured regularly over a given period of time. This method establishes a trend of measured distances over time, which can tell whether movement is indeed occurring in an area (Olivar, 2001). However, the drawback of this type of monitoring is the scarcity of data, since measurements are carried-out at spaced-out interval. The technique is also ineffective in recognizing impending landslides. Thus, immediate response to landslide occurrences is slow. A technique that can provide measurements on a daily basis and can thus be used to succesfully recognize impending landslides is the use of extensometers. Extensometers are instruments that provide a measure of the ground movement by measuring the displacement of a device from a fixed reference point. The data from extensometers can thus be the basis for a quick response to an impending landslide. Figure 2 shows the design of the extensometer used in PNOC-EDC geothermal fields. Currently, an extensometer is installed in the Tower No. 7 area of LGPF.

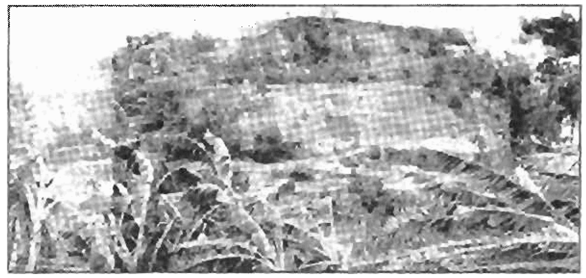

**Photo 1. View of the Upper Mahiao quarry after a reduction of the upper load and benching of the slope face has been effected.**

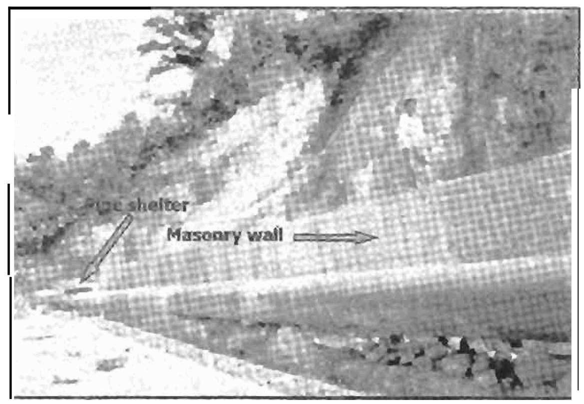


**Photo 2. View along the Mahagdong-MGRD1B access road. Photo shows the newly constructed masonry wall. Also visible is the pipe shelter that was constructed to protect the pipeline from landslides.**

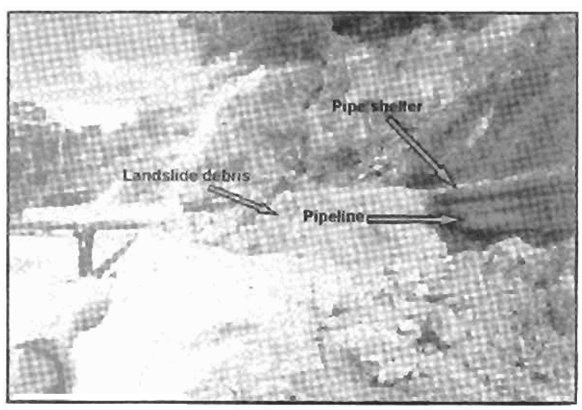


**Photo 3. Taken along the Mahanagdong to MG-RDIB access road. Shown is a landslide which covered the pipeshelter and pipeline. The pipe shelter protected the pipe from damage.**

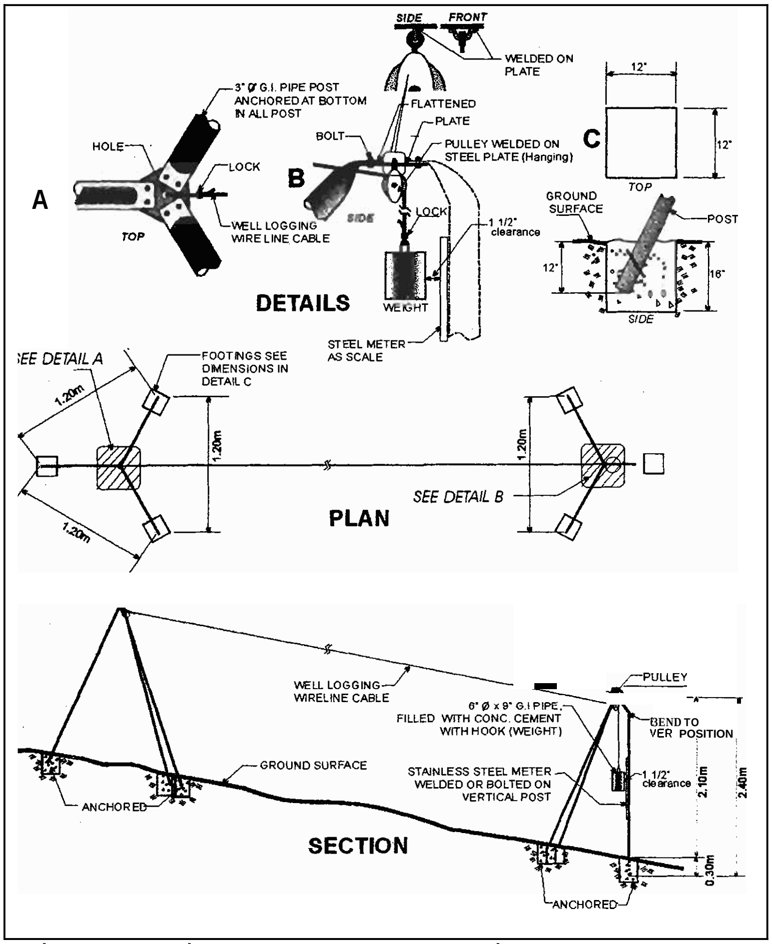


Figure 2. Design of extensometer installed in Tower No. **7 location.**

## 5.0 THE LANDSLIDE HAZARD ASSESSMENT OF TOWER NO. 7 LOCATION IN LGPF AND THE FCDS LOCATION ABOVE UPPER E PAD IN MGPF

The following are case studies of two areas in PNOC-EDC geothermal fields, underwhich assessed for landslide hazards. These are Tower No, 7 location in LGPF and the FCDS route above pad **E** upper in MGPF.

### 6.1 Tower No. 7

Tower No. 7 of the Leyte Geothermal Production Field is located at about 590 masl, northwest of the Malitbog power plant (Fig. **3).** The tower site is flanked by steep slope on both sides about three meters away from the wall face. The rocks beneath the tower are mostly colluvium and/or debris materials, which is composed of highly- to moderately-weathered boulders of volcanics and breccias, underlain by highly weathered tuff.

During the height of Typhoon Auring last February 2001, a huge landslide occurred at the slope below the tower location. Rainwaters could have seeped through cracks near the edge of slope and along the periphery walls which were previously created by an earthquake (Arreza, pers. comm.). The concrete wall surrounding the tower is now at the edge of the landslide crown (Photo 4). Moreover, after the landslide, the cracks have widened and threatened the stability of the tower base and periphery walls (Fig. 4).

To mitigate the risk, engineering measures consisting of reinforced concrete masonry wall was built to protect and prevent the slope from further sliding (Photo 5). The site is also continuously being monitored using an extensometer that was locally fabricated (Photo 6).

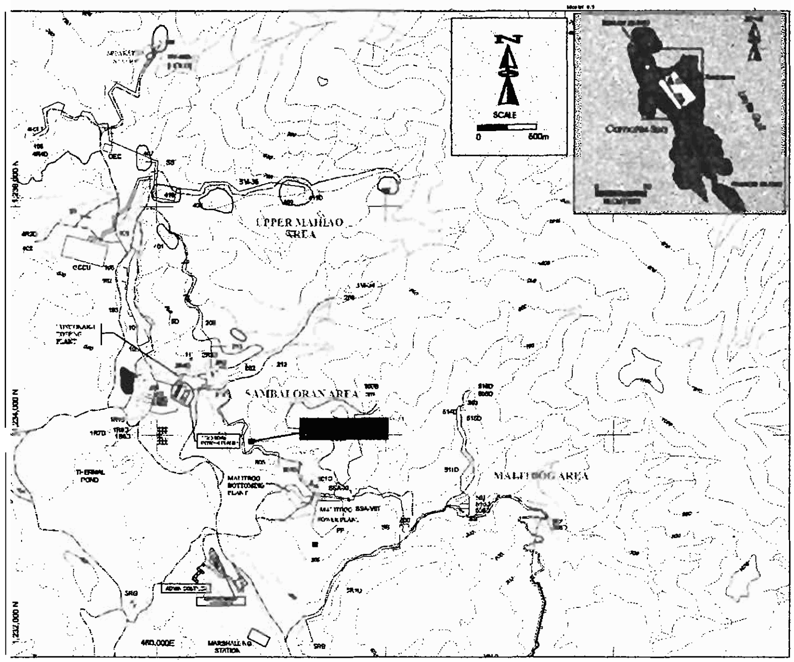


**Figure 3. Location map of Tower 7, Leyte geothermal production field.**

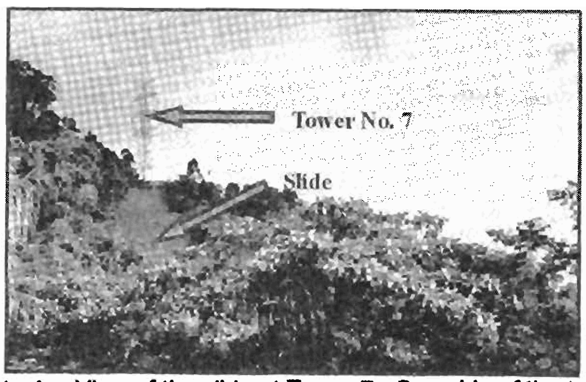


**Photo 4. View of the slide at Tower 7. One side of the tower footings is now at the edge of the slide crown.**

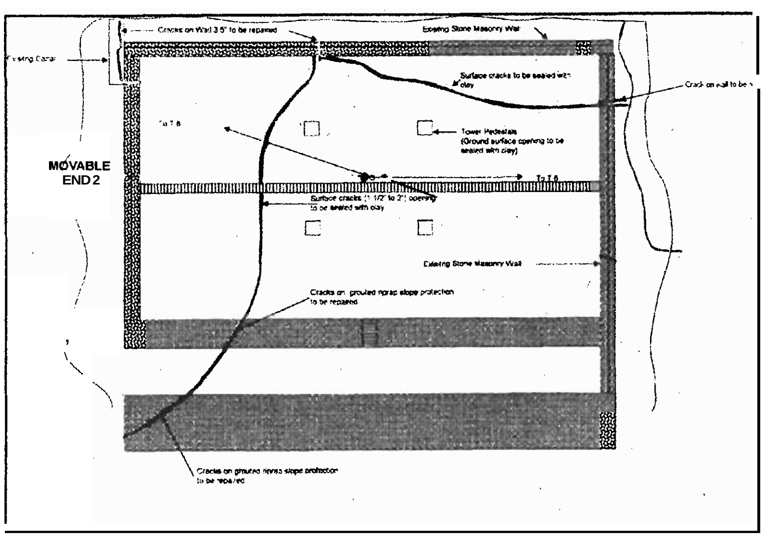


**Figure 4. Top view of Tower 7 and the visible cracks opened up during May 8, 2000 earthquake.**

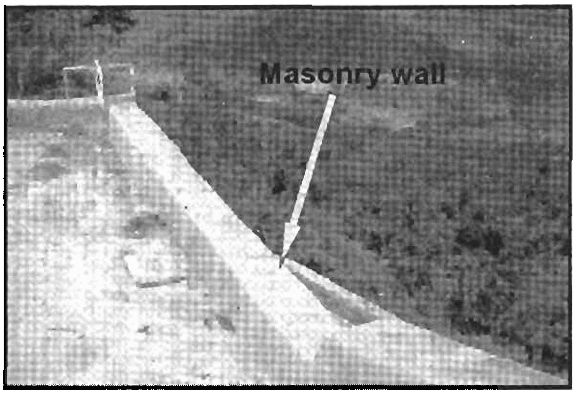


Photo **5.** View of Tower 7 and the newly constructed masonry wall.

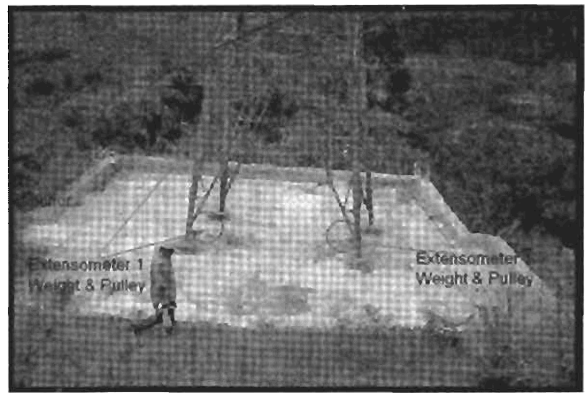


Photo 6. Location of landslide monitoring equipment at Tower 7, South Sambaloran.

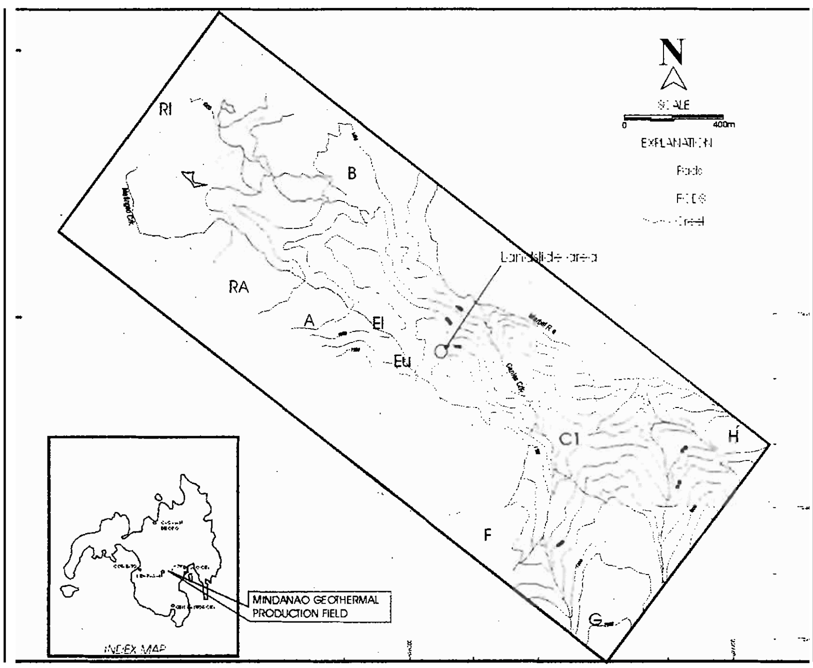


**Figure 5.** The 701 has. Mindanao geothermal production field showing slide area above E upper Pad

## 5.2 FCDS Route Above Pad E Upper, MGPF

A portion along the Fluid Collection Disposal System (FCDS) route of the Mindanao II Geothermal Project (M2GP) above Pad E upper (Fig. 5) was assessed for slope failure potential (Pioquinto, 1998). The slope face is composed of intensely altered and highly to moderately weathered volcanics with boulders about 7-10 m above the road embedded in a weak sandy to clayey matrix which is overlain by weak semi-solid colluvial materials. The area is therefore prone to sheet slides or movement of shallow surficial debris (Zaruba and Mencl, 1982) and rockfalls/rockslides which are landslides with rocks as primary component. Table 7 shows the detailed instability calculation for this location and Photo 7 shows the above FCDS route above pad E upper before the installation of the pipeline.

On the basis of the above assessment, reinforced concrete pipeshelters were constructed after the pipelines were built to protect them from potential landslides. As a result, the FCDS lines in this portion were safeguarded from any damage during the 1999 and 2001 landslides. Photo 8 shows the area (now with pipeline and pipe shelter) after the Occurrence of the landslide.

Table 7. Example of determination for instability rating.

| Location: Jump-off point above upper E pad | | | |
|---|---|---|---|
| **Factor** | **Weight** | **Field data** | **Rating** |
| A1. Slope gradient (°) | EI | 52° | A |
| A2. Slope height | EI | <25 m | B |
| A3. Slope direction | I | towards | A |
| A4. Deformation intensity | I | great | A |
| A5. Age of deformation | I | recent | A |
| A6. Activity of deformation | EI | active | A |
| A7. Type of slope material | VI | landslide material/clayey earth | A |
| B1. Rock type | VI | volcanic breccia (?) | D |
| B2. Weathering grade | VI | highly weathered | B |
| B3. Discontinuity orientation | VI | - | - |
| B4. Discontinuity spacing (cm) | EI | - | - |
| B5. Rock mass | VI | massive but altered | E |
| B6. Presence/condition of faulting | VI | inactive,< 50m | C |
| B7. Presence of clay and or acid-altered grounds | VI | predominantly clay alt'd | A |
| C1. Type of vegetation | I | no cover | A |
| C2. Density of vegetation | VI | very low | A |
| C3. Type of land use | EI | road | B |
| C4. Type of protection facility | VI | none | A |
| C5. Drainage facility | EI | canal | C |
| D1. Seepage | EI | always damp | C |
| D2. Permeability of top soils | I | low | A |
| D3. Presence of water course | VI | none | E |

Summing up the total of A's,B's,C's,D's and E's with respective EI,VI and I weights :
ratings of A with EI+VI weights = 6

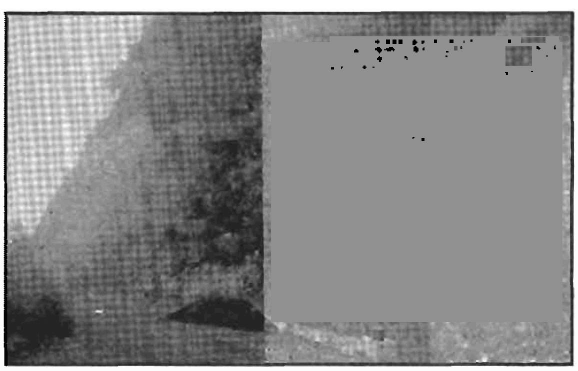

Photo 7. View of the FCDS route above pad E upper (MGPF) before the installation of pipelines and pipe shelters. An escarpment at left poses hazards to rock fall as boulders could be loosened from the slope face. A landslide could also originate between the clay-altered layers and the overlying residual soil or colluvium outcropping at left.

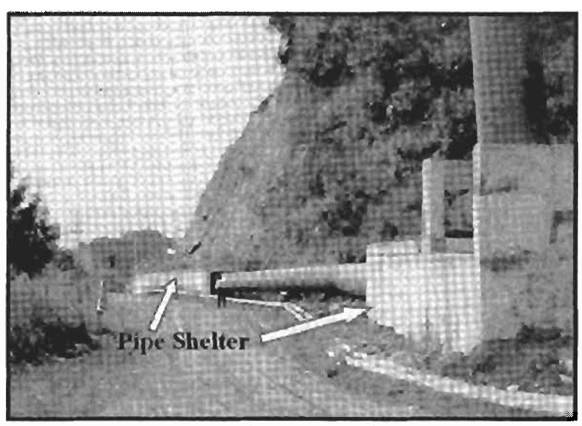


Photo 8. View of the FCDS route above pad E upper taken when the pipelines were already in place together with the pipe shelter. A landslide has occurred as evidenced by the remaining debris (most were already cleaned-up). The pipe shelter protected the pipelines.

## 6.0 CONCLUSIONS

The two case studies demonstrated the successful and direct application of landslide hazard assessment in PNOC-EDC geothermal fields. The technique implemented is simple yet reliable in which it effectively predicted the occurrence of landslide in the case of the M2GP FCDS route landslide assessment. The timely installation of pipe shelters had shielded the pipelines from landslide damages in 1999 and 2001.

The two case studies also showed the PNOC-EDC experience in the assessment. and remediation measures through the application of various engineering methods like masonry walls, and also vegetative slope stabilization.

Simple and cheap tools that are locally fabricated such as extensometers are also utilized in follow-up monitoring. This is currently being conducted in Tower No. 7, which is very critical in order to determine if it is still at risk of toppling.

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