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GEOLOGICAL HAZARDS AND GEOTECHNICAL ASPECTS IN GEOTHERMAL AREAS, THE EL SALVADOR EXPERIENCE

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ABSTRACT

Geodynamic processes affecting the Earth's surface give rise to ground movements of various characteristics, size and speed. The most common and widespread are the landslides, encompassing gravitational processes that occur on the slopes. The action of gravity, the progressive weakening of the materials, mainly due to weathering (the process of disintegration and fragmentation of the constituent minerals of rocks), and the performance of phenomena such as heavy rains and earthquakes cause the ground motion are relatively common in the geological environment. These processes are falling short of potential geological hazards as they may cause economic and social damage to affect human activities and constructions.

The implementation of measures to prevent risks from landslides, mud flows or rock falls is most effective when the processes occur at small scale, i.e., with dimensions that will address their control, but when it comes to large movements, usually impossible to control, and in these cases, the only possible measures are the prevention and land use restrictions. This is not the case for a geothermal development, where the resource is located in a volcanic setting with areas of hydrothermal alteration, paleo landslide scarps and seismic activity. Mitigation works are implemented in order to manage the geological hazards taking into account the geotechnical aspects of the soils and ground surface of each geothermal area.

Geological hazard´s mapping is being done in each of the geothermal fields, in order to have a data base, which includes the mitigation works performed each year. This allows Lageo´s personnel to monitor each year the evolution and to repair any if it is necessary.

1. INTRODUCTION

The existence of geothermal areas in El Salvador is mainly due to it's location along the tectonically active margin between the Cocos and Caribbean tectonic plate, and to it's proximity to the North American and Caribbean plate margin (Figure 1). The geologic and tectonic processes of both plate margins contribute directly to generating the main engines for geothermal resources: heat and rock permeability. The volcanoes along the Central American volcanic arc supply the heat and the tectonic

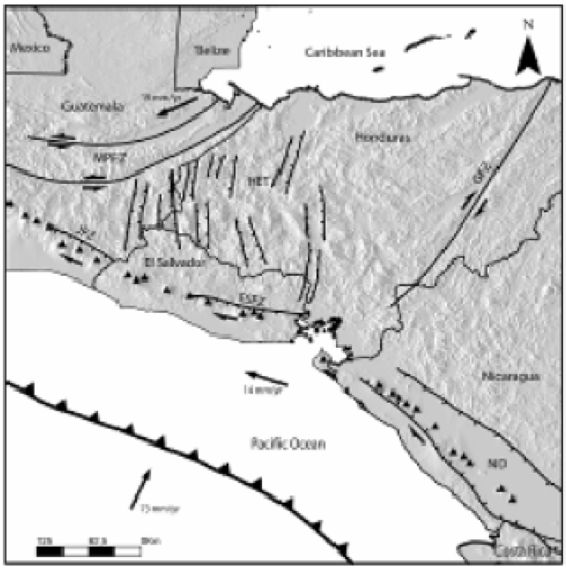

FIGURE 1: Location of El Salvador with respect to the main tectonic features in northern central America. MPFZ: Motagua-Polochic fault zone, which is the contact of the Caribbean plate to the south and North American plate to the north; JFZ: Jalpatagua fault zone and ESFZ: El Salvador fault zone which are right lateral strike slip faults; HET: Honduras extensional terrains; ND: Nicaragua depression. The contact between the Cocos plate to the south and the Caribbean plate to the north is represented by the saw-toothed line along the Pacific Ocean, which marks the location of the subduction trench

interactions between the plates generate the faults and seismicity that induces secondary permeability. Intense tropical precipitations contribute to the third parameter needed in a geothermal resource: geothermal fluids.

Unfortunately, the same factors that contribute to the existence of geothermal resources also contribute to the main geological hazards that affect the development of geothermal fields.

In El Salvador, most high temperature geothermal resources are directly linked to an active or dormant volcano (Figure 2). The location of a geothermal site on the flank of a volcano makes it vulnerable to various volcanic hazards of an erupting volcano. Besides these hazards volcanic products such as ash or lavas, also contribute to geotechnical problems such as slope stability, erosion control and seismic amplification and in addition, the steep terrain of most volcanoes also represents a problem not only for construction purposes but for slope failures.

Volcanoes occur at places where the earth's crust has enough permeability for magmas to raise to the surface. These areas are often marked by extensional tectonics that generate moderate to strong earthquakes which in addition to causing damage of infrastructure by ground shaking, can also generate landslides that can become fluid and produce debris flows that affect areas far from the steep flank of the volcanoes.

Rainfall in El Salvador is concentrated in six months of a year, during which total amounts of precipitation of greater than 2,000 mm are often observed. Precipitation is produced by intense thunderstorms that last a couple of hours or can be in the form of monsoonal rains that last for days on end. In both cases and particularly in areas with pronounced slopes, when the soil gets saturated it will become unstable and possibly generate landslides or debris flows.

Taking into account these geologic challenges, planning for the development of a geothermal resource has to include several studies that determine the potential geologic hazards that may affect a

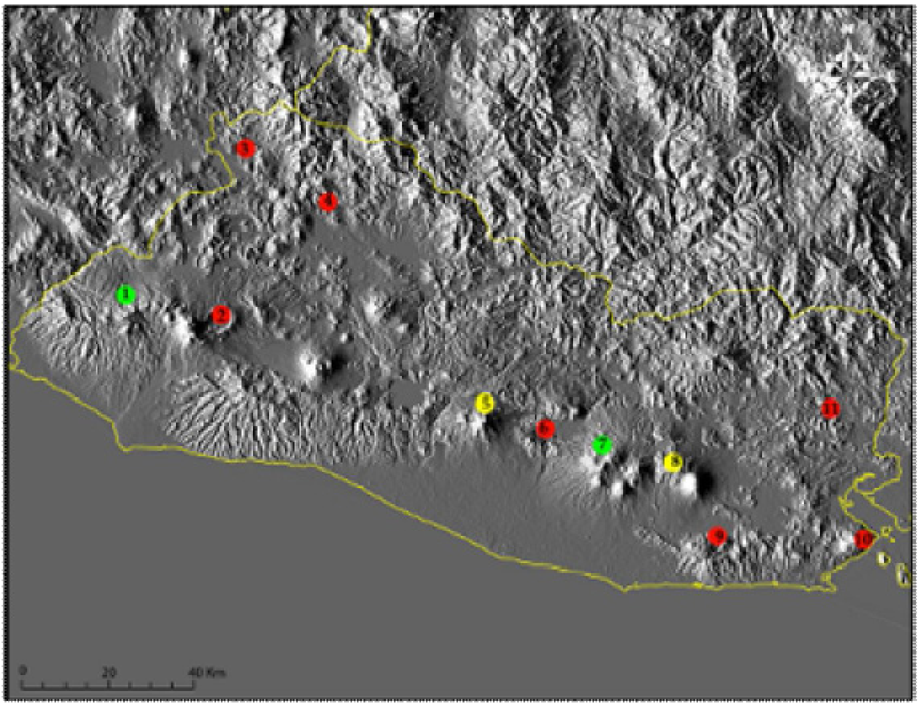

FIGURE 2: Geothermal areas in El Salvador. 1) Ahuachapán; 2) Coatepeque; 3) Metapán; 4) Chalatenango; 5) San Vicente; 6) Obrajuelo; 7) Berlín; 8) Chinameca; 9) Chilanguera; 10) Conchagua; 11) Santa Rosa de Lima. Green circles denote areas where production is in place, yellow circles where both surface exploration and drilling have been done and red circles where only surface exploration has been carried out

geothermal power plant and its associated infrastructure in the short and long term. These studies may include very detailed geotechnical analysis of a construction site (well pad, power plant, pipelines, etc) to regional studies such as seismic or volcanic risk studies.

The present study reviews the different geologic hazards that are present in El Salvador's geothermal areas and discusses how these hazards can affect a geothermal field, from the early stages of development of a field to a mature field in production. Specific examples from Chinameca and San Vicente fields will help illustrate things to take into account in the development of a new field on the flank of a volcano. Examples from the Ahuachapán and Berlín geothermal fields will illustrate problems faced in producing fields.

2. GEOLOGIC HAZARDS

2.1 Seismic hazards

Seismic risk can be defined as the potential of economic, social and/or environmental loss caused by a seismic event that may occur in a specified period of time. In order to determine seismic risk of a given site, analysis of seismic hazards and infrastructure, environment and social vulnerability have to be completed.

Seismic hazard analysis tries to determine the expected earthquake ground motions at any point on the earth but also has to include the study of site related earthquake hazards, such as: ground deformation, liquefaction, landslides, ground shaking amplification and even tsunamis and floods. The vulnerability of infrastructure, the environment or society refers to how well these can withstand and recover from an earthquake.

In the case of a geothermal resource hazard assessment has to determine:

- Location of potential seismic source zones that could generate damaging ground motions at the site.
- Earthquake recurrence and location of events as well as the expected ground motions.
- Location of active faults in the field.
- How ground motion can be affected by soil and topographic conditions at the site.
- Potential areas of landslides, liquefaction and ground deformation.

In El Salvador's producing geothermal fields, Ahuachapán and Berlín, in addition to understanding how well buildings, infrastructure and equipment will respond to ground shaking a good understanding of how wells and pipelines might be affected by a strong earthquake. Both geothermal fields are close to local fault seismic sources and can be affected by regional earthquakes generated at the plate boundaries.

Even though seismic activity in El Salvador is very high, during the short history of production of the Ahuachapán and Berlín geothermal fields have only been affected by one large earthquake. The January 13th 2001, magnitude 7.6 earthquake which was located approximately 100 km south of the Berlín geothermal field was responsible for the 850 deaths, produced strong ground shaking that damaged thousands of rural homes, and generated hundreds of landslides all along the active volcanic range of El Salvador.

Apart from landslides and rockslides that affected the Berlín geothermal field, strong ground shaking caused by the main event and subsequent strong aftershocks caused a break in one of the 115 kV power lines and the shut down of one of the main turbines at the Berlín geothermal field, closest to the epicentre of the earthquake (approximately 90 km). In Ahuachapán (approximately 180 km from the epicentre), the power plant also shut down several times due to strong ground shaking associated to the main earthquake and aftershocks. Nationwide, the earthquake caused a blackout for several hours after the main shock but the first power plants to come on line were both geothermal power plants.

Several months after the January 13th 2001 earthquake an increase in thermal activity was noticed at the Agua Caliente fumaroles of the Ahuachapán geothermal field. This increased activity expanded the thermal area and caused the death of coffee and shade trees in previously cultivated areas. Similar activity was not observed at other fumaroles in Ahuachapán or Berlín geothermal fields.

2.2 Volcanic hazards

A volcanic hazard refers to any potentially dangerous volcanic process (e.g. lava flows, pyroclastic flows, ash). Volcanic risk is any potential loss or damage as a result of the volcanic hazard that might be incurred by persons, property, etc. or which negatively impacts the productive capacity/sustainability of a population.

It is very important to consider that in the case of a geothermal power plant any impact that forces to shut down the power plant can be considered that it "negatively impacts productive capacity". Typically, volcanic hazards increase the closer you are to an eruptive center. However, in the case of a geothermal power plant one would have to consider how falling ash produced at a distal erupting volcano could affect running machinery or electrical installations that could conduce to shutting down the power plant.

Depending on the type of volcano, there are several volcanic processes that are considered to be volcanic hazards, amongst these:

- *Volcanic earthquakes*: the ascent of magma to the surface generates seismic activity that is associated to the movement of magma and to the fracture of rocks. The 1917 eruption of San Salvador volcano triggered earthquakes of moderate magnitude, associated to local faults.
- *Ballistic impacts*: during an eruption large pieces of rock broken form the eruptive conduit (ballistics) or pieces of semi solid magma (bombs) are ejected in a ballistic projection around the crater's rim. The impact of this can be severely destructive and can even generate forest fires.
- *Ash fallout*: any eruption of a volcano that produces an eruptive column will produce ash, very small fragments of magma, rocks and crystals that because of their light weight will travel suspended in the air for some distance. Usually, the more energetic the eruption the farther the ash will travel. Ash can have different impact on the environment and infrastructure depending on that amount of ash that accumulates and its composition.
- *Volcanic gases*: these are produced in non-eruptive volcanoes as well as in eruptive volcanoes. Gases emitted through fumaroles areas are a normal in geothermal fields. However as magma starts to intrude the composition of the gases change and become much more acidic and therefore much more corrosive. The impact of corrosive gases to geothermal installations can be caused by acid rain, which occurs when an active volcano emits a plume of gas through its crater and it rains, or gases can get mixed into the geothermal system, effectively changing the composition of the fluids and making them much more corrosive.
- *Lava flows*: if an eruptive volcano produces lavas flows, these can be severely destructive especially of buildings and infrastructure are these are not mobile.
- *Debris avalanches*: Debris avalanches are massive landslides, where a sector of a volcano collapses. Even though this is a very destructive process, as it completely obliterates everything in its path, such events rarely occurs during the lifetime of a volcano.
- *Pyroclastic surges and flows*: these are fluidized masses of rock fragments and gases that move rapidly down slope in response to gravity. They can form in several different ways: when an eruption column collapses, or as the result of gravitational collapse or explosion on a lava dome or lava flow, or as a result of a volcanic blast. The difference between a pyroclastic surge and a flow is the density of the material. Pyroclastic surges are low density flows that can overcome topographic barriers, while pyroclastic flows are denser flows that are usually limited to topographic lows (drainages, creeks, valleys).

Both Ahuachapán and Berlín geothermal power plants are located on the flanks of Holocene volcanoes with no history of eruptive activity in the past 500 years. However, both volcanoes can be characterized as active volcanoes due to their present state of activity (fumaroles, seismic activity) and because of geologic evidence that demonstrate that eruptive activity has occurred in the recent geologic past.

In order to understand the potential hazard of a renewed eruptive activity and the vulnerability of these established power plants efforts should be made to try to determine the specific volcanic hazards that each volcano represents, determine the potential areas that could be affected and establish the probability of occurrence of each hazard. Once this has been achieved, measures (insurance or other financial measures) could be taken to minimize the economic impact of loss of production caused by an eruption.

In new areas, where there has been limited development of the field, knowledge of the types of hazards present, areas to be affected and recurrence of events should be taken into consideration in the final layout design of the power plant and superficial installations.

During the productive history of both Ahuachapán and Berlín geothermal fields there have only been two eruptions from different volcanoes in El Salvador. One of these eruptions occurred in 1975 at San Miguel volcano in eastern El Salvador. This eruption was a minor magmatic eruption that produced lava fountains and ash that did not have any effect on the Berlín geothermal field (30 km east of San Miguel volcano), because development of this field was in its early stages and ash was not distributed at these distances. A more recent phreatic eruption in 2005 occurred at Santa Ana volcano, which is approximately 20 km east of the Ahuachapán geothermal field. A small amount of ash did reach the geothermal field, but it was quickly washed away by torrential rains associated to Hurricane Stan.

Even though these minor eruptions did not affect geothermal installations or production, they serve as examples of potential hazards from distal volcanoes. If large amounts of ash should fall on a productive geothermal field, it could potentially have severe effects on production as ash particles could damage turbines, electrical circuits, collapse roofs and contaminate water reservoirs.

2.3 Landslides

Landslides, or earth movements can be generally described as the movement of earth and/or rocks, together with vegetation and any object that is found on a sloping surface of the earth. Many classifications and definitions of landslides have been described in the literature, amongst these: rotational landslides, translational landslides, rockslides, mudslides, rock falls, etc.

There are several internal factors that contribute to generating landslides including: slope (gravity), types of material and how altered is the original material. Usually landslides are triggered by external factors such as earthquakes, heavy rainfall or strong vibration, but sudden events can occurr without any of these occurring.

Once these earth movements are triggered the area that it affects can vary greatly and will depend on the material that is moving, topography and water content. Damages caused by landslides are severe as they can bury or completely destroy any infrastructure in its path.

Volcanoes in El Salvador are characterized by their steep slopes and abundance of young volcanic products; they are subject to tectonic activity and an abundance of rainfall that occur as prolonged monsoon type rainfall or as intense tropical thunderstorms. These conditions and the fact that geothermal areas located on their flanks generate a lot of hydrothermal alteration make the slopes of volcanoes ideal places for generating different kinds of slope stability problems.

The Berlin geothermal area is the geothermal area most affected by landslides in El Salvador. The steep terrain, hydrothermally altered areas and strong rainfall are the main cause for a series of problems including translational landslides, rock falls, soil creep and mud slides. During most rainy seasons these are generated but during major meteorological events the problems intensify.

On October 1998, Hurricane Mitch caused a series of landslides, debris flows, and rock falls that affected the town of Berlin, closed down the main roads leading to the town and the geothermal power plant and caused some damages to geothermal installations. The majority of these were located in the steep slopes of the volcanoes, south of the geothermal power plant and closely associated to the presence of road cuts, hydrothermally altered and fumarolic areas. Photos of instability phenomena recorded during Hurricane Mitch are shown in Figure 3.

In addition to the heavy rainfall in the Berlin geothermal seismic activity has also caused landslides. The 2001 earthquakes that affected El Salvador during January 13th and February 13th caused at least twenty small rock falls and landslides, most of which were located along the main road to the city of Berlin and the geothermal power plant (Figure 4). Rock falls also fell on well pad TR-2, which is located next to an almost vertical 25 meter slope.

In order to mitigate some of these problems, there has been a strong effort to try to understand these hazards by mapping landslide features, identifying steep slopes where landslides can be generated and drainages that could become channels for debris flows. In addition to these, strong investment has been made in the construction of minor civil works meant to mitigate rock falls, increase capacity of

FIGURE 3: Mud flows in the Berlin Tecapa Volcano. a) along a drainage, and b) along the slope close to the Berlin town

drainages and protect geothermal infrastructure such as well pads, geothermal fluid pipelines and road cuts.

2.4 Debris flows

Debris flows are a special kind of mass movement that is characterized by a fluidized flow of mud and/or rocks that is channelized in a drainage and incorporates almost everything in its path. Debris flows can be caused by different natural events, including volcanic eruptions, heavy rainfall and failure of dammed water. Once the debris flows are formed and channelized they will travel for long distances within the drainage as long as there is sufficient slope and the flow remains in the channel. Once the channel opens the debris flows splay out and deposit the solid material it carries, forming a slurry that hardens into a very strong deposit.

Debris flows are common in the steep terrains of El Salvador, where they are mostly caused by heavy rainfall but have also been caused by earthquakes and volcanic eruptions. In the steep slopes of a volcano, damage is limited to the channel of the drainage it flows in but in the area where the debris flow splays damage spreads to a fan like area at the end of the channel.

Debris flows affected the town and geothermal area of Berlin during the rainfall caused by hurricane Mitch. These were generated by landslides on the steep slopes of the volcano close to fumarolic areas and as the debris flows travelled down the drainage channels they were observed to jump from one

FIGURE 4: Several rock falls located a) West of TR4, Berlin Field, b) Road Mercedez Umaña-Berlin City, c) West of well TR11, occurred during the two earthquakes in January 13th and February 13th 2001.

channel to another channel because the original one could not handle the volume of the flow. In all, approximately 33 people lost their lives due to debris flows that affected temporary housing on the streets of Berlin.

More recently, on November 2009 very heavy rainfall fell on San Vicente volcano, where development of a geothermal area is underway. The intensity of the rainfall, almost 300 mm in a few hours, generated numerous landslides on the steep slopes of the volcano which then became debris flows that travelled for several kilometres within drainage channels. Several towns and main roads where affected as they were in the path of the debris flow or at the base of the channel, where the debris flow splayed out and deposited material.

These debris flows did not affect any geothermal infrastructure, mainly because development is in its early stages and there are only three well pads constructed in the area, but also because these are located on high ground compared to the drainage channels. However, roads interconnecting the well pads were completely destroyed in places where they drainages where the debris flows had travelled in.

Even though successful efforts have been made to control debris flows in countries such as Japan and Norway by reinforcing channels in order to contain and direct the debris flows, the high cost of construction of these major civil works limits the possibility of mitigating them.

The lessons learned from experiences at Berlin and San Vicente indicates that the best way to not be affected by debris flows is to stay away from them. These means that efforts have to be made to map the drainages that can be affected by debris flows and identify areas where these will display and deposit all their material. Any major infrastructure, such as a well pad or power plant should be located on high ground, away from these channels. Roads that have to cross these drainages can be reconstructed but geothermal pipelines that cross the same drainages have to be built high above the drainage floor.

2.5 Hydrothermal explosions

Hydrothermal explosions, although not common have been registered at several geothermal fields around the world, including El Salvador. These explosions are associated directly to fumarolic areas where water can accumulate or in areas with a high water table. They are not very recurent but in some cases such as El Zapote fumarole in the Ahuachapan geothermal area, have been reported after every strong rainfall season.

These type of explosions are low energy explosions associated to geyser type activity or caused by a sudden burst of accumulated steam. They mainly expel hot wet mud and rocks that are found inside the fumarole that caused the explosion and their deposits only reach a few tenths of meters away from the vent.

Even though hydrothermal explosions are low energy explosions they can be deadly and cause damage to infrastructure if located near a vent. A hydrothermal explosion that occurred in 1990 at the Agua Shuca fumarole area in the Ahuachapan geothermal field, killed close to 20 people that lived right next to the mud pool that was the source of the eruption.

Since these types of eruptions are associated to fumarole areas, they generally do not represent much of a hazard to geothermal infrastructure. However, in order to reduce any possible hazard, all visible fumaroles areas and areas of hydrothermal alteration should be mapped in detail so that they are taken into account when construction is being planned.

3. GEOTECHNICAL ASPECTS

In any type of building it has to be considerate the investigation of the subsurface conditions, trough the study of the mechanical characteristics of the soil or rock deposits where the work will be build, in order to provide information about the nature and suitability of the subsurface materials.

Generally the data necessary for geotechnical analysis is about the geology (stratigraphical and structural), description of the nature and extend of the subsurface materials, mechanical characterization of soil and rocks, slopes stability and information on groundwater. The type and the thickness of soil, the depth to bedrock may be determined to know the foundation conditions. It should be also some inferences about geological hazards, effects of seismic amplification, the bearing capacity, potential settlement and swelling.

The local geology in the geothermal fields from El Salvador due its volcanic origin of the deposits produces high slope lands, different types of rocks (lava flows, pyroclastic deposits, lahars deposits, etc). Also is common to find fumaroles and hydrothermal alteration areas, where the mineral from original rocks are altered to clay and oxides minerals mainly. That means that in these alteration areas the slopes have low stability.

The main works that have to be building in a whole geothermal project are the power plant, the drilling platform, the steam and water pipelines and the access roads. In the following paragraphs the focus is on some examples about geotechnical problems related to the local geology, in the building of the drilling platforms, the infrastructure of a power plant and the others surface installations.

3.1 Well pads

Most of the geothermal fields in El Salvador are usually located on the northern flanks of the Quaternary volcanoes. Therefore it is common to build a drilling pad on a mountainside, on slopes as high as 25 %, associated to soils with hydrothermal alteration. This is the case for wells TR19´s, TR18´s and TR17´s in Berlin, Chi3´s in Chinameca and SV4 and SV5 in San Vicente geothermal field. (Escobar, 2008). Great amount of civil work is invested such as concrete and gabion walls and are built in the surrounding areas, drainages and slopes to assure the infrastructures. Usually half of the pad is built with filling materials to compensate the excavated area to build a flat surface, where most of the surface installation is located.

Another common problem mostly encountered in the Berlin and Ahuachapan geothermal fields with pads built on average slopes of 18-20%, is that the pads terrain are associated to scarps of paleo landslides combined with soils with hydrothermal alteration of great extent. This is the case for wells TR-2, TR-7 and TR-10 where Fumaroles such as El Tronadorcito, El Tronador and El Bálsamo-TR-6 are located. Greater amount of investment on civil works is done in order to give a higher stability to the platforms before starting drilling and afterwards to protect the steam and water pipe system.

An example of such works is well TR-2 which was drilled from January to June 1978. At the end of 1992 and the beginning of 1993 twenty small diameter wells with 50-100 m depth were drilled in that platform in order to stabilize the surroundings of the cellar (Figure 5). Cement slurry was injected in the wells to seal the fractures where gases and steam flowed up to surface. At the end of the work 70 % of the hydrothermal manifestations decreased around the well. Similar works were performed in other pads (TR-7, TR-10, etc).

In the year 2010, the cellar of well TR2, evidenced degradation of the cement and steam started coming out from some small fractures located on the northern walls (Figure 6). Figure 7 shows temperature distribution measured at 50 cm depth. Figure 8, shows the evolution of the slope since the year 1992 to 2010. In the year 2010, the southern slope was repaired with concrete shots and steel mesh to retain any rock fall. Several landslides in the surrounding walls of the scarp, occurred throughout the years 1998, 2001, 2003, 2007 and 2010. Most of them were stabilized.

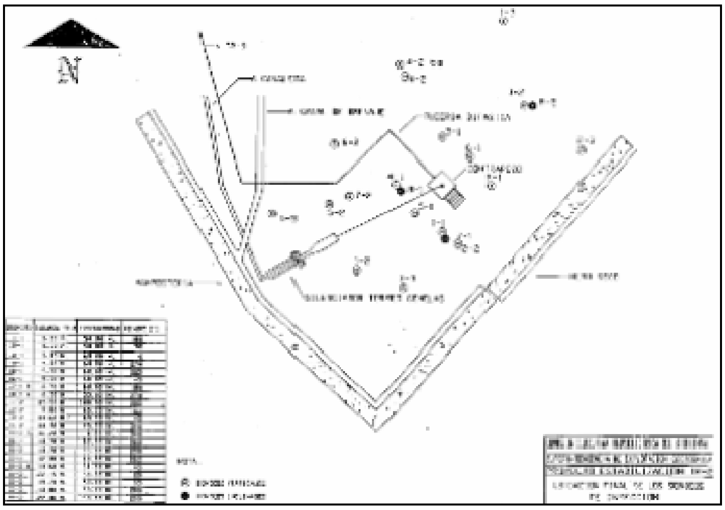

FIGURE 5: Small diameter wells location in TR-2 platform (CEL, 1993)

Figure 9 shows several gabion walls built from year 1990-1991 to stabilize the western slope of the TR2 pad. By the year 2010, this wall is completely covered with vegetation and several landslides have occurred in the years 1998, 2001, 2003, 2007 and 2010. Mitigation works started in the year 2003 and Figure No. shows the gabion walls built to retain any rock fall, mud flow and landslides. In 2011 the civil works will continue to stabilize the recent landslides occurred at the end of 2010.

FIGURE 6: Damages on the cellar, well TR-2. Hydrothermal manifestations in the northern corner

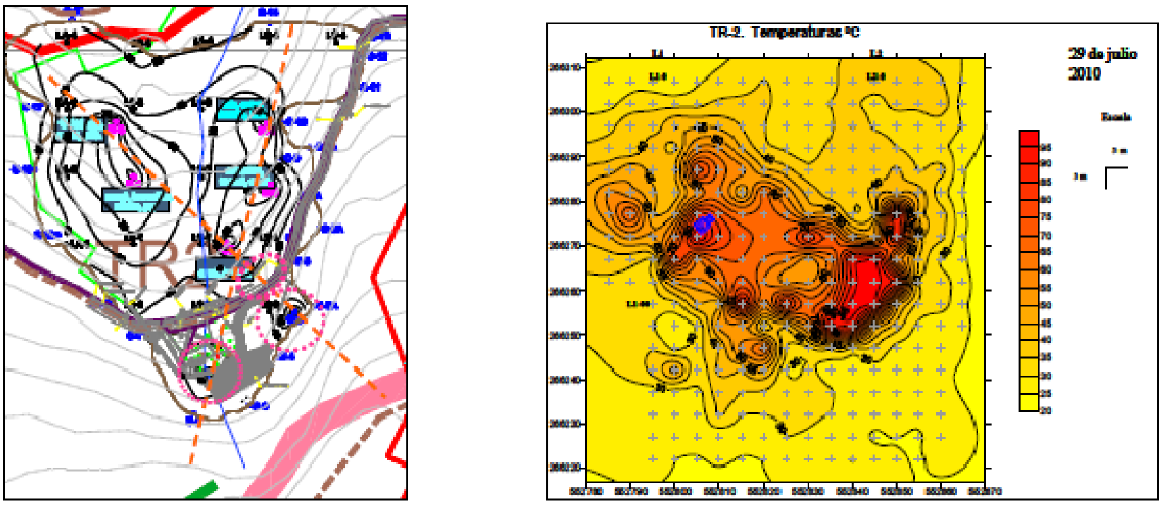

FIGURE 7: Temperatures (in °C) measured in July 2010; notice temperatures are higher than 90°C in the southeast slope and where the well is located. It follows a structural trend NW-SE and NE-SW

FIGURE 8: Western slope of platform TR2 in the year 1990-1991; several gabion walls were built

3.2 Access roads

In the case of the platforms, some of the hillsides where the access roads are built have very high slopes and excavations and filling materials are necessary. Due to the heavy transport traffic where heavy equipment is moved, before, during and after the drilling job, the road needs enough load capacity and an adequate design. The access roads need slopes well constructed to assure a good drainage system and a wide curve to mobilize big trucks. In some cases the road is located on top of a slope formed by several layers of pyroclastic rocks, mainly unconsolidated (pumice fall, ash fall, etc). When weathered layers, hydrothermal alteration or paleosoil is present, the deposits do not have good behavior to the loads. An instance of this is the slope located in the access road to TR-19 wells. It remained stable even during the time when heavy equipment was moved (Figure 10).

3.3 Power plant

During the construction of the Berlín geothermal power plant problems related with the local geology were encountered. In the Berlín power plant site, the foundation was set up in a fresh and fractured lava flow with more than 5 meter thick. This made the excavations difficult but it was managed by cementing all the fractures and only a meter was excavated because of the hardness of the rock. In some sites east and west of the power plant problems related to foundations or expansive soils are present.

FIGURE 9: Gabion wall at TR2 as seen from the east side. The dam is built in sections, 2, 4, and 5 m high, as seen on the picture. b) The gabion wall seen from the north side

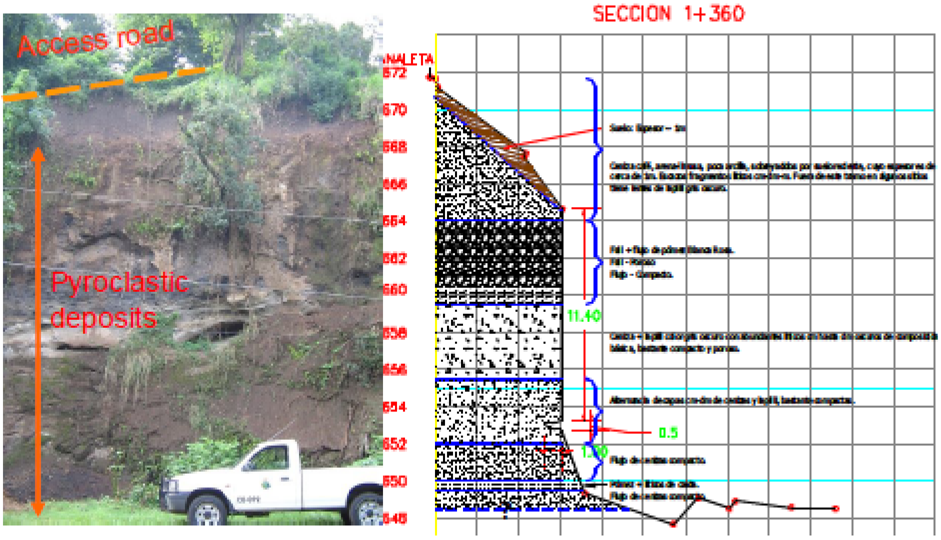

FIGURE 10: The access road to TR-19 pad, located on top of the pyroclastic deposits

3.4 Steam and water pipelines

In the geothermal fields from El Salvador, the main problems related to the foundations of the pipe lines bases are related to the stability of slopes and the soil erosion. In October 2007, a small landslide affected the reinjection line to the TR-19 wells, near to La Flecha area, where a debris flow material slide over underlying deposit formed by clays produced by hydrothermal alteration. The bases of the pipeline were displaced around two meters (Figure 11).

The steam gathering system near the power plant which carries all the steam from production wells TR2, TR9, TR4´s, TR5´s, TR17´s and TR18´s, cross the fumarolic area called El Tronador which is associated to a landslide scarp. A gabion wall was built south of the pipelines to protect them from any rock fall and landslide (Figure 12).

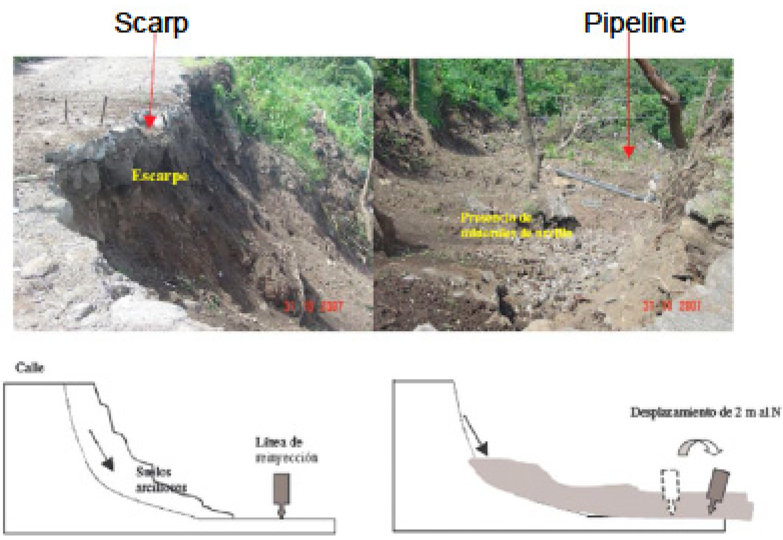

FIGURE 11: Photos and scheme of the landslide that affected the reinjection pipeline near to the La Flecha hydrothermal alteration area, Berlín geothermal field in October 2007 (From Henríquez and García, 2007)

FIGURE 12: a) The gabion wall is adjusted and not leaning against the pipeline. b) The gabion wall is build to secure the pipeline (following the outer side of the wall) against slides. A rock fall has already hit the wall (red circle), without making any signs of destruction. c) The gabion wall along the pipeline down slope seems sufficient to prevent new damages from slides. The fundaments of the pipeline were partly damaged in a previous slide

FIGURE 13: El Tronador Fumarolic area with steam gathering system near the Berlin power plant. A long gabion wall was built on the southern flank of the pipeline

FIGURE 14: a) Mitigation works on the northern slope of the gathering system TR17s/TR18´s to injection well TR19´s after a landslide occurred in the year 2007. b) Gathering system along the slope close to TR19 injection well

4. CONCLUSIONS

El Salvador's geothermal fields are located next to active volcanoes where geological hazards are permanent threat to infrastructure and personnel. Seismic, volcanic and heavy rainfalls contribute to generating several different hazards that have to be taken into consideration when developing a geothermal resource.

Detailed mapping as well as statistical analysis of all known geologic processes should be carried in order to understand what areas can be affected and what the probability of occurrence each one of the processes has in a given year. This analysis will help in the understanding the geologic risk of the resource and will help prevent later problems. Existing fields and power plants may have been built without full knowledge of geologic hazards, in which case mitigation and risk management efforts have to be made in order to lessen the impact of any given hazard

Many of the geotechnical problems faced in geothermal areas are related to the nature of geothermal activity. The large content of clays, anomalous temperatures and corrosiveness of fumaroles and hydrothermal alteration zones make them difficult for construction. Special the slopes located in these areas normally have low stability.

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