"DETERMINATION OF LANDSLIDES AND FAULTS IN THE TRANSMISSION LINE CARIBLANCO-SAN MIGUEL, COSTA RICA 2009"

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LiDAR, CIR images, Combined Flight, Digital Elevation Model, Orthophotos.

ABSTRACT

The unstable and geologically hazardous area of Poas Volcano (Costa Rica) was affected by a 6.2-degree magnitude earthquake in January of 2009. The consequences of the earthquake were shocking. The urban area of Cinchona was almost devastated and its residents are being relocated. Road links were severely damaged, major landslides blocked them for many days after the earthquake.

This article summarizes the actions carried out after the earthquake in order to analyze the effects on the infrastructure and population and to define the actions to rebuild the affected area and avoid future risks.

After of the seismic, many problems were detected in different structures of the line transmission Cariblanco-San Miguel, affecting its different circuits

Technical professional staff of the ICE carried out inspections via air and land from the. Upon receipt of this first inspection information, critical areas were assess by means of quick Orthoimages and Digital Elevation Models from a combined flight, which includes laser scanner and digital camera, able to simultaneously obtain immediately Digital Images and LiDAR data in order to start to develop plans of action to give this line temporarily reliability and propose a definitive solution.

Giving special attention to the electric lines, an assessment of each of the sites was made between the towers at 37 and TS 62 to qualify its condition on-site. As methodology of identification of the seriousness of the situation keeps the symbology of green for all towers that have not obvious problems, and therefore are not mentioned in the present report. Yellow conditions qualify those sites with any type of affection, but not undertake short-term stability of the Tower. Finally, the Red condition applies to those sites where required immediate action for having commitment in its stability in the short term.

It is remarkable that all access to the towers roads are severely damage, with many cracks, cement folders collapsed and the main roads of domestic routes as no. 126, does not exist at the moment.

QUICK ORTHOIMAGES AND DIGITAL ELEVATION MODEL OUTSET

Since the photogrammetric flights, and thus the cartography, *Orthophotos* and DTM are obsolete and do not cover the entire country, and in order to analyze the affected area optimally, a combined photogrammetric flight was chosen to obtain digital *Orthophotos* and precision DTM to evaluate the damage caused in the area due to the earthquake, specially in the transmission line power.

The combined photogrammetric flight consists in simultaneously taking aerial images and *LiDAR* data to determine the position and intensity of each one of the points on which the laser beam reflects on the ground. The purpose is to obtain colour digital *Orthophotos* and real projections of the *Orthophotos*, which will be simultaneously generated by merging the imaging and land elevation data.

The media used to capture the data included: a large format digital camera DMC-Zeiss Intergraph - Digital Matricial Camera consisting of: 8 optic lenses (4 Panchromatic/4 Multi-spectral), an electronic image sensor: CCD matrix, a Navigation system: ASMS (Airborne Sensor Management System) and a GPS and INS system, and a laser system for remote measuring, which allows for quick, accurate terrain modelling, composed of a GPS receiver and an inertial system (provides the position, trajectory and orientation of the laser), a transmitter, and a scanner that enables a very dense and accurate cloud of points with XYZ coordinates to be obtained, known as a *LiDAR* system (LIGHT DETECTION AND RANGING).

The area of activity measures approximately 500 km2, for which the following flight plan with East-West sweeps was designed.

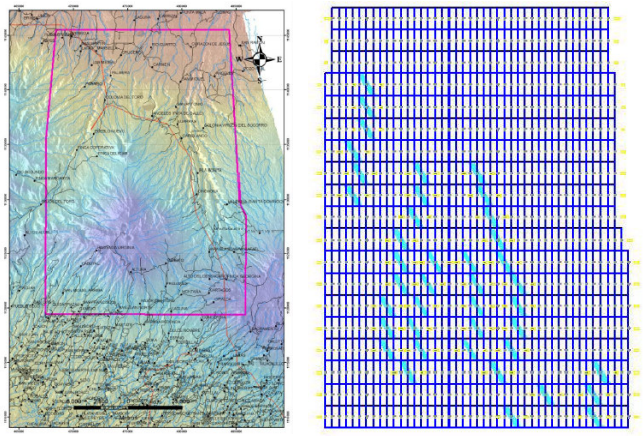


Fig.1 - Planning Graphics-

The flight was performed at the beginning of April, with a total of 87 flight lines.

Panchromatic, RGB and infrared 15 cm images and a cloud of LiDAR points were taken simultaneously obtaining a density of 1pt/m2.

Fig. 2 - Example of images taken-

Once Aerotriangulation was completed, we continued with the photogrammetric process by rectifying the images, with the aid of a DTM. The model automatically-generated from the entire cloud of points from the *LiDAR* data was obtained by using an automatic filter process that allows the points corresponding to the terrain to be selected, forming the DTM.

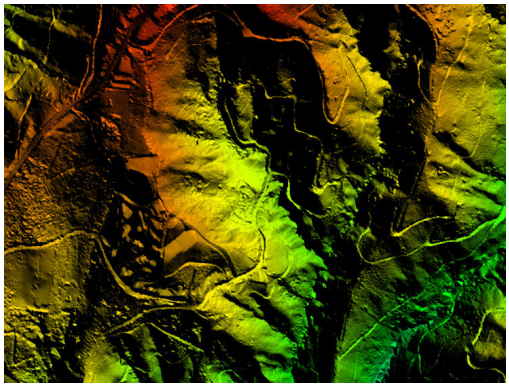


Fig.3.- Automatically generated DTM-

The precision with which the DTM was obtained from the gross *LiDAR* data did not exceed 15 cm in altimetry and 25 cm in planimetry.

The result obtained almost automatically corresponds to an orthorectified RBG and CIR image derived in subsequent studies.

As the human eye is more sensitive to changes in shade of red, and from the perspective of the photo geological analyses, landslides, soil, alignments, forested mass and outstanding aspects of the rock formations that have been discovered because of this seismic event can be better differentiated.

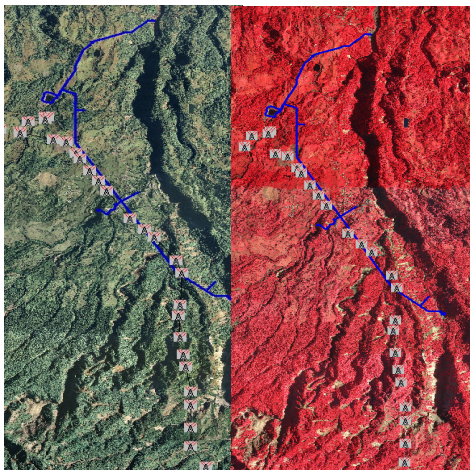


Fig.4 -RGB-CIR Comparison

With respect to the landslides, those involving the different public works of the Cariblanco Project and the Transmission Line in the segment of the earthquake area were analyzed.
Polygonal landslides were marked and the internationally used landslide categorization was not performed.

A total of 282 landslide polygons were identified, with the majority concentrated in the area of the right bank of the Sarapiquí River, where the project is located. (Table1)

PUBLIC WORKS AFFECTED	AMOUNT OF LANDSLIDES
INTAKE AREA	8
TUNNEL AREA	21
PRESSURE PIPING AND MACHINE BUILDING	53

Table 1. Detail per work.

The remaining 200 landslides located on the banks of the Sarapiquí will present a serious indirect danger to the stability of the Machine Building area and to the damming produced with rains in this area for several years until said Sarapiquí banks are stabilized.

With regard to the alignments, all straight-line alignments were marked, which signal every fluvial network, old scars from faulting, the cracks caused by the earthquake, within the landslides where the rock that was revealed, the cracks and outstanding straight-line geomorphologic characteristics were marked, for a total of 1166 alignments. Then, using the ArcGis 9.3, from a subroutine called Rose Diagram, the preferential directions of these alignments were analyzed. (Table 2)

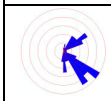
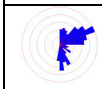
DIRECTION DIAGRAM	AREA	COMMENTS
	Machine building	Two predominant directions: N15 E and S20E
	NE part of Sarapiquí River near the machine building	Two predominant directions: NE and SE
	Sarapiquí River, North-Central part	One predominant direction: NE
	Sarapiquí River, Central part	One predominant direction: S20E
	Cariblanco Project intake area	Two predominant directions: NE and S
	NW area of the Pressure Piping	One predominant direction: NE
	Oscillation Tank and Transmission Line area	Two predominant directions: NE and SE
	Cariblanco substation area	Two predominant directions: N and N30E
	West central area of the Line and Tunnel	One predominant direction: NE
	Southwest area of the map	One predominant direction: NE

Table 2 -Direction analysis by sectors.-

Two dominant directions were determined from the preferential directions analysis of the alignments: North South and SE, which can be corroborated with what we observed in the field. Photos have been included below. (Fig. 5, Fig. 6)

Fig.5. "NS"direction cracks. San Miguel-Cariblanco-Cinchona area

Fig. 6. "NE" direction cracks. San Miguel-Cariblanco-Cinchona area

There are 85 alignments with both preferential directions (NS and NE); they may affect the intake area the following two PI's of the tunnel. We recommend that the tunnel be inspected in these areas for micro fractures, as it was one of the most highly-affected areas. We suggest a high resolution, *LiDAR* laser scan inside the tunnel to rule out micro fractures.

Another area that was very affected as regards number of alignments (341) is the Oscillation Tank and Pressure Piping area. Detailed inspections are recommended to check in the two predominant directions described to locate cracks and their length for engineering assessment.

The remaining 740 alignments are significant for the monitoring studies in coming years to determine the threats and vulnerabilities to other public works, as they will be the new landslides and sinking of terrain.

CIRCUITO CARIBLANCO-SAN MIGUEL

Tower TS 37

The Tower is founded on metric thickness soils that previously had problems of stability, demanding at the time the construction of protected rocks on its side that after the event collapsed and towards the West sector presents at least 5 levels of fractures that determine dowels with moving eastward and affecting the leg C. However other fractures in the way of access put at risk the West side of the structure.

The structure presented slight curvature in the amounts due to settlements and differential displacement in the legs. The vertical component these offsets vary from 10 to 15 cm. This curvature in the Tower elements fails in imminent danger of collapse to the structure.

Issues of access due to over two metres wide at the way tension cracks were detected.

Evaluation of the Tower: yellow condition

Fig.5. Tower TS 37 LT Cariblanco-San Miguel, possible site of replacement. Picture from digital camera in *LiDAR* sensor incorporated.

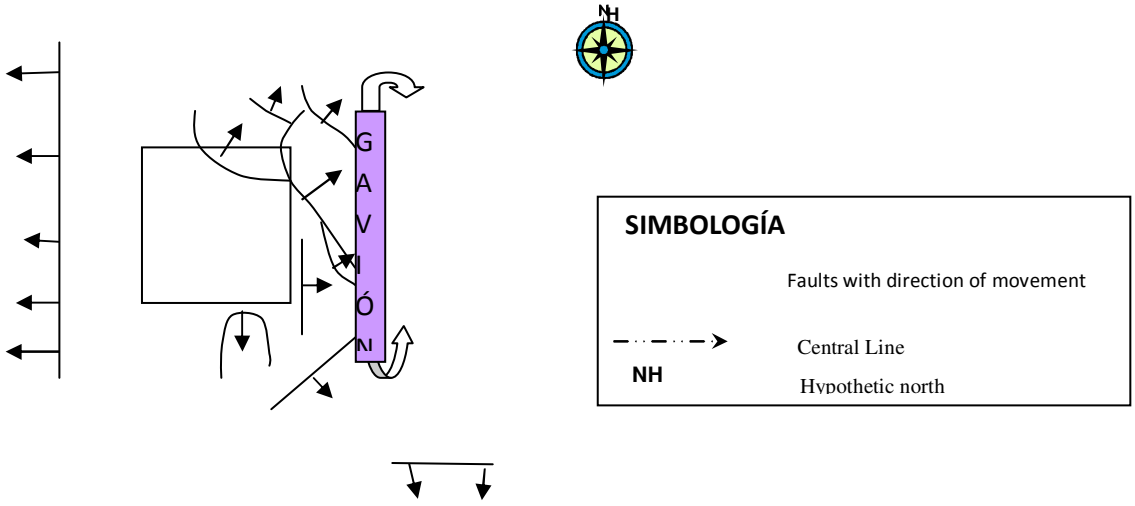


Fig 6. Schema's break in the Tower 37

Fig. 7- Tower 37 LT Cariblanco – San Miguel. Horizontal and vertical movement in the terrain and structure. Picture from Ing. Bayardo Selva Mora.

Tower TA 38

Cracks were observed during the visit to assess by specialists in Geotechnics. Problems detected by the nearby volcamiento of stones covered and because it is a structure in angle should pay you attention. The Tower not presented buckling or failure problems in any element.

Evaluation of the tower: Yellow condition.

Fig.8 Tower 38 LT Cariblanco-San Miguel. **Picture from** *LiDAR* 2008-2009

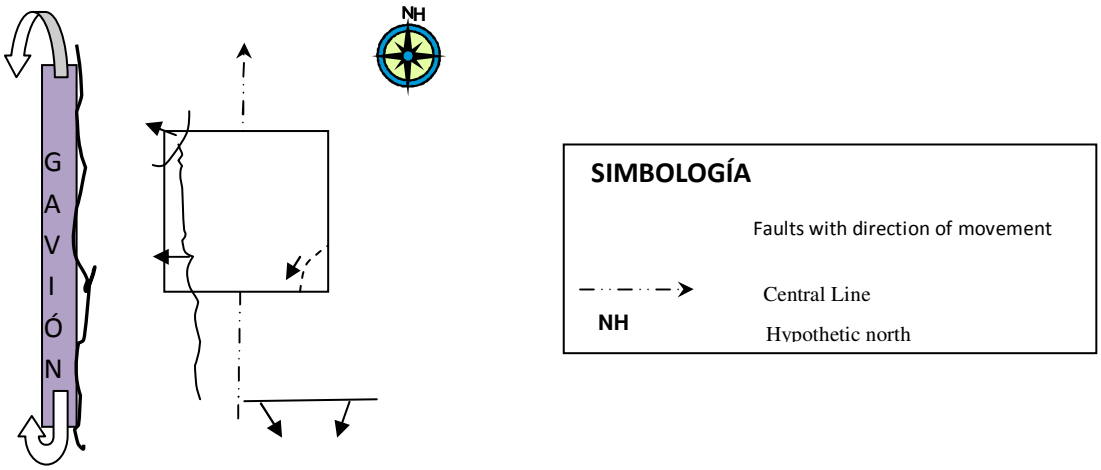


Fig.9. Schema of fracture in the Tower 38.

Fig.10. Tower 38 LT Cariblanco-San Miguel. Note the horizontal movement in the terrain and possible fracture. Ing. Bayardo Selva Mora. Y Cristiam Valerio

Tower TA 39

There were numerous cracks in the lining of concrete tower site that reflect the existing field and small landslides in legs oriented in the direction of Cariblanco (North).

Curvatures and important deflections had been observed.

Evaluation of the tower: Red condition.

Fig.10. Tower 39 LT Cariblanco-San Miguel. **Picture from** *LiDAR* 2008-2009

Fig.11 Tower 39 LT Cariblanco-San Miguel. Picture from Ing. Christiam Valerio.

Tower TA 40

There were numerous cracks along the way before the Tower, in the area of the towers and surrounding found cracks multi-direction crossing the legs, extending to the East side with small dowel, showing the entire block where the tower knocked over.

These surface fractures have openings that vary from cm to some dm; direct measurement of its depth exceeds 1.8 m, by which the risk that fractures extend beyond the level of Foundation, this thickness based decamétrico and development of these volcanic soils.

Elements bent in the enclosure or frameworks to top-level legs were observed that demonstrate displacement and differential settlements between the legs of the tower.

These deflections in the Tower elements fail in imminent danger of collapse to the structure and provided not differential movements between the legs to increase this issue continue presenting can cope with.

Evaluation of the tower: Red condition.

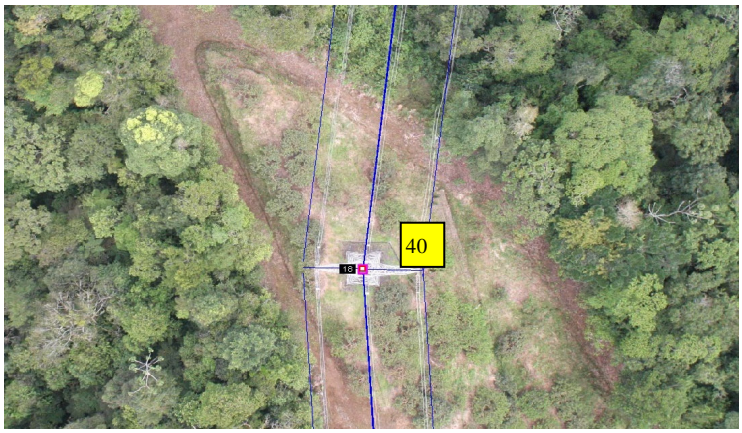


Fig.12. Tower 40 LT Cariblanco-San Miguel. Picture from *LiDAR* 2008-2009

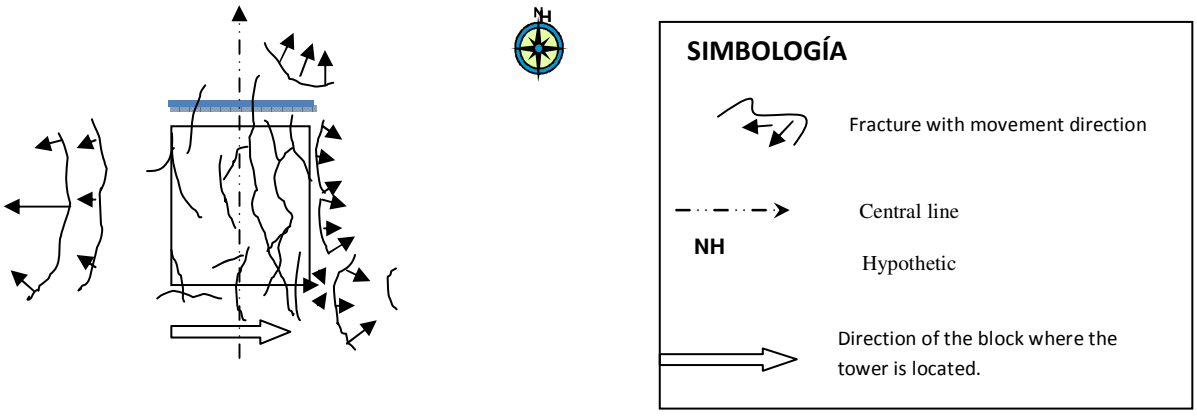


Fig.13. Cracks near the legs of the TowerTower 40 LT Cariblanco-San Miguel

Tower TA 41

These surface fractures have openings that vary from cm to some dm; direct measurement of its depth exceeds 1.8 m, by which the risk that fractures extend beyond the level of Foundation, this thickness based decamétrico and development of these volcanic soils.

During the visit numerous cracks were observed before the tower. The site and surrounding area found cracks multi-direction. Elements bent in the enclosure or framework to top-level legs that demonstrate displacement and differential settlements between the legs of the tower were observed.

These deflections in the Tower elements fail in imminent danger of collapse to the structure and provided not differential movements between the legs to increase this issue continue presenting can cope with.

Evaluation of the tower: Red condition.

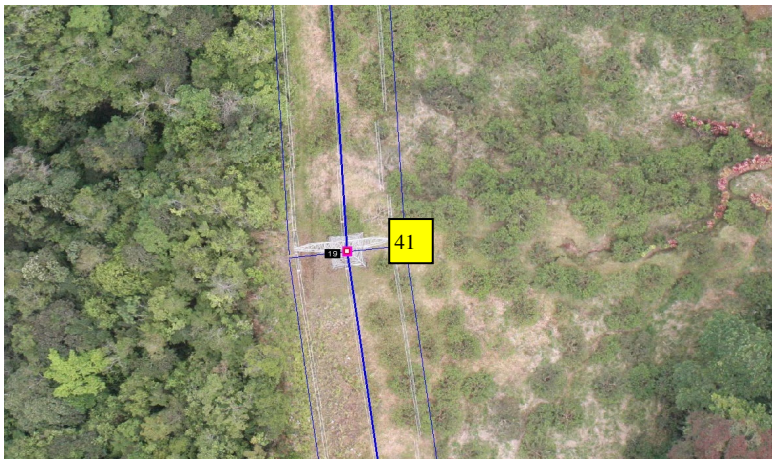


Fig.14. Tower 41 LT Cariblanco-San Miguel. **Picture from** *LiDAR* 2008-2009

Tower TS 62

Noted that the tower is founded on soil without any anchor to rocky substrate whereas the profanity of this, previously had stability is treatment problems overcome with the placement of a gabion on the East side of the structure, which stopped working after of the earthquake and is currently dump being floating shape.

The tower site is affected by at least four major fractures and their associated fractures affect structure components either directly or by material mobilized towards them.

The parallelism between major fractures determines dowels with movement westward, featuring internally very low stability. Horizontal and vertical movements of the legs of the towers were observed. The Tower does not present any element deformations or visible inflections.

Evaluation of the tower: Red condition.

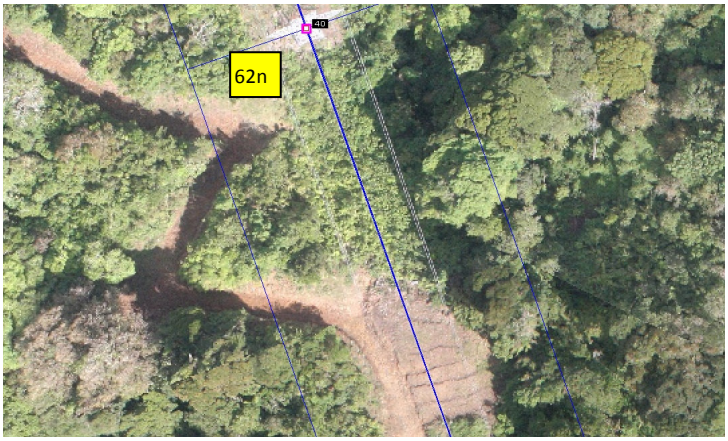


Fig.15. Tower 62 Picture from *LiDAR* 2008-2009

Fig.16. Fractures to the West of tower 62, obvious movement towards East, causing small landslides that put pressure on the structure. Picture from Geol. Ronald Valverde.

Tower TS 68

During the visit were cracks in the ground to approximately 10 m of the legs of the tower.

Evaluation of the tower: Yellow condition.

Fig.17. Tower 68 Picture from *LiDAR* 2008-2009

Tower TS 74

Significant cracks near the feet of the tower were observed during the visit. Ran a collapse approximately 2 m between legs A and D.

Problems of access due to significant cracks were detected.

Evaluation of the tower: Red condition.

Fig.18. Tower 74. Picture from *LiDAR* 2008-2009

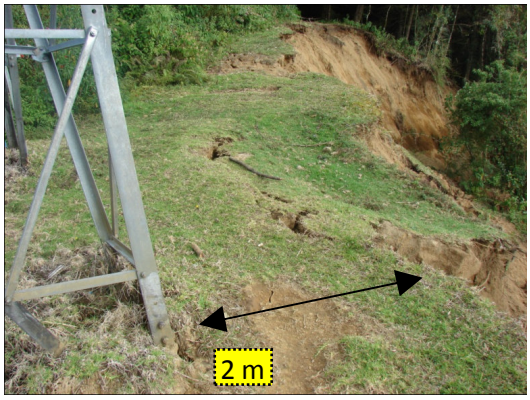


Fig.19. Tower 74. Slope close to the tower. Picture from Ing. Bayardo Selva Mora

Summary of the diagnosis of towers between Cariblanco-Carrizal of transmission line section Cariblanco – San Miguel

State of transmission towers in the TL San Miguel- Cariblanco:

Stretch	*Number of towers*	*Code*	*Number of Towers*	*% affected line*
Toro-Cariblanco	29	Critic	0	0
		Reparation	0	0
		Stable	29	100
Cariblanco-San Miguel	118	Critic	6	5.08
		Reparation	6	5.08
		Stable	106	89.83

SUMMARY

Millions of earthquake happens around the world every year; and while it is true that some areas are more vulnerable to the risk of an earthquake, no area is completely exempt. Therefore, both local and central governments are seeking representations of the territory to be able to study it, model it and perform damage analysis, to then be able to create architectonic and engineering models to minimize damage in the case of future earthquakes.

By using the most advanced technologies, such as *LiDAR*, assessment studies of damages produced by earthquakes can be conducted with high precision, as these technologies can measure the structures and damages both horizontally and vertically. Thematic maps can be constructed through these technologies which would then allow decisions to be made about the most compromised and vulnerable areas.

Eight landslides threaten this work in the intake area and part of the right bank of the Sarapiquí River covered by this study.

In the tunnel area, there are 21; the tunnel does not appear to be affected because it is subterranean. However, the road infrastructure and transmission line have been affected.

A total of 53 were detected in the Oscillation Tank, Pressure Piping and Machine building, meaning the public works and road infrastructure are endangered and highly vulnerable.

The remaining 200 landslides are located predominantly throughout the Sarapiquí riverbed, and will present significant stability problems for the slopes, causing greater landslides of forested mass, soil and rock formation, causing damming as an indirect effect of rain and other seismic events; these pose a threat to the Machine Building and the waters beneath this basin.

A total of 1166 alignments were identified and may be associated with fractures, faults or other geomorphologic aspects present in the Cariblanco Project public works and road infrastructure in these areas.

In the Intake area, 85 alignments with both of the preferential directions (NS and NE) were located; these may affect the intake area and the following PIs of the tunnel.

The Oscillation Tank and Pressure Piping area was greatly affected (341 alignments). Detailed inspections are recommended to check in the two predominant directions described to locate cracks and their length for engineering assessment.

Whereas the deterioration of sites and structures affectation, we recommend relocate the Towers 39 and 45 in the shortest time possible, to better mechanical physical condition of soils, but with slope instability sites, whereas the impossibility of better conditions in the towns, causing the recommendation to treatment of soils in the previous form pre-selected sites.

The other visited towers, require short and medium term implementing measures which extended life, ranging from waterproofing and drainage of grounds to the treatment of the soil by injection or greater severity consolidation methods that reduce the apparent instability structure.

Damages presented the stretch of transmission line, from its proximity to the population of Marseille to the zone Carrizal, concludes the need to relocate the circuit geese-San Miguel, so to start the route using data base from *LiDAR* and images and the environmental impact study, looking for land more geological stability and moderate slopes, as the right site of the Sarapiquí River Bank area pending.

CONCLUSIONS

This work demonstrates the importance of react to a disaster such as an earthquake, with fast geographic information, accurate and high resolution. This information has been supplied by an air platform with multiple sensors aboard (digital camera - LIDAR, video) with robust direct orientation equipments and applying contrasted methodologies.

The post-processing of information goes in the concept of "fast", based on download information, process at the base of operations and developing quick products (Ortho-DEM), with fewer requirements that allows decision making.

Analysis of the digital data in GIS tools and an experienced workflow has given some remarkable results as shown in the article. The concept of fast, new geographic products Orto-DTM-DSM, digital workflows, interpretation by GIS tools and significantly the concept of multifunctionality of information (population, infrastructure, forest, hydraulic,...) are essential in this type of actions.

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References:

ALVARADO, G.E., 1988. Comentarios sobre las avalanchas en el río Toro, P.H. Toro II. -8 págs + 2 planos, Inf. Interno ICE, Departamento de Geología.

ALVARADO, G.E., 2000. Los volcanes de Costa Rica: Su geología, historia y riqueza natural. -xv + 269 p.; EUNED (2da edición); San José.

ALVARADO, G.E. & CLIMENT, A., 1985. Informe sismológico para la etapa de avance a la factibilidad (P.H. Toro II). -46 págs. + figuras, Anexo B., Departamento de Geología.

ALVARADO, G.E. & SCHMINCKE H.-U., 1994. Stratigraphic and Sedimentological aspects of the raintrigged lahares of the 1963-1965 Irazú eruption, Costa Rica. -Zbl. Geol. Paläont., I, 1993 (1/2): 513-530; Stuttgart.

ALVARADO, G.E., MORALES, L.D., MONTERO, W. CLIMENT, A. & ROJAS W., 1988. Aspectos sismológicos y morfotectónicos del extremo occidental de la Cordillera Volcánica Central, Costa Rica. -Rev. Geol. Amér. Central, 9: 75-98.

ALVARADO, G.E. & SALANI, F.M., 2004: Tefroestratigrafía (40 000 – 2000 a.P.) en el sector Caribe de los volcanes Barva, Congo y Hule, Cordillera Central, Costa Rica. – Revista Geológica de América Central, 30: 59-72.

ALVARADO, G.E. & SALANI, F.M., 2009: The 6100 B.P. violent phreatomagmatic eruption of Hule Maar, Costa Rica. – IAVCEI-CVS-IAS 3 IMC Conference, Malargüe, Argentina, 2 págs.

ALVARADO, G.E., SOTO, G.J., ZÁRATE, E. & ZELEDÓN, R., 1989. Evaluación del riesgo volcánico del Poás sobre las obras del P.H. Toro. -44 págs. + figs., Dirección de Planificación Eléctrica, ICE.

ALVARADO, G.E., MORA, R. & PERALDO, G., 2003. The June 2000 Arancibia Debris Avalanche and Blockslide, Costa Rica. -Landslide News, 14/15: 29-32.

Alfonso Gómez Molina, J. Delgado García y J.M. Azañón, 2004 "Morphological Terrain classification and analysis using Geostatistical Techniques ".

Colomina, I., Giménez, M., J.J.Rosales, J.J., Wis, M., Gómez, A. y Miguelsanz, P. (2004). "Redundant imus for precise trajectory determination. The International Archives of the Photogrammetry",

Delgado, J., Cardenal, J. y Gómez, A., 2000. "On the use of the geostatistical estimation techniques to the generation, debugging and analysis of Digital Surface Models"

Alfonso Gómez, Javier Serrano, Daniel Casalprim, 2005 "Generation of a DTM based on Lidar Data for the definition of Hydraulic Models "

ARREDONDO, S.G. & SOTO, G.J., 2006: Edad de las lavas del Miembro Los Bambinos y sumario cronoestratigráfico de la Formación Barva, Costa Rica. – Revista Geológica de América Central, 34-35: 59-71.

AVILÉS, F., 2009. P.H. Cariblanco. Dique de protección a casa de máquinas. Memoria de cálculo. -16 págs., Inf. Interno ICE.

ALFARO, A., MICHAUD, G. & BIOLLEY, P. 1911: Informe sobre el terremoto de Toro Amarillo, Grecia. Anales del Centro de Estudios Sismológicos de Costa Rica. -Tipografía Nacional, pp. 33-41.

AMBRASEYS, N., 1995: Magnitudes of Central American earthquakes 1898-1930. -Geophys. J. Int., 121:545- 556.

ARIAS, O., 2004: Marco Geotectónico. En: Estudio Geológico-Geotécnico para la Factibilidad del P.H. Toro III. -Inf. Interno ICE. Vol. 1, pp. 23-25.

ARROYO, I.G. & ALVARADO, G.E., 2002. Evaluación geotectónica de la falla San Miguel y alrededores, enfocada en los proyectos hidroeléctricos Cariblanco y Toro III. -Inf. Interno ICE, Área de Amenazas y Auscultación Sismo-volcánica. 25 pp. + plano.

BARRANTES, J., 2006. Estimación de la amenaza de represamiento en el río Sarapiquí para el análisis devulnerabilidad en la Casa de Máquinas del Proyecto Hidroeléctrico Cariblanco. IX Seminario Nacional de Geotecnia, noviembre 2006 (documento digital).

BARRANTES, J. & JARQUÍN, M.F., 2005. Amenaza de represamientos provocados por deslizamientos enlas márgenes del río Sarapiquí en los alrededores de las obras del P.H. Cariblanco. -60 págs., Inf. Interno ICE, UEN Diseño.

BARQUERO, R., 1995. Proyecto hidroeléctrico Laguna Hule. Estudio sismológico para la etapa de

Factibilidad. -11 Págs., Inf. Interno ICE, OSV 95.09-ICE.

BARQUERO, R., 2000. P.H. Toro III. Estudio sismológico etapa de Factibilidad. -10 págs., Inf. Interno ICE, Exploración Subterránea.

BARQUERO, R. & CLIMENT, Á., 2002. P.H. Toro III: Estudio sismológico y de amenaza sísmica etapa de Factibilidad. -19 págs., Inf. Interno ICE, Exploración Subterránea.

BARQUERO, R. & SOTO, G.J., 2003. Estudio de amenaza sísmica y volcánica para la subestación transformadora Cariblanco y su derivación a la línea alterna. -17 págs., Inf. Interno ICE, C.S. Exploración Subterránea.

BARQUERO, R., BOSCHINI, I. & ALVARADO, G., 2007. Estudio sismo-tectónico para el P.H. Toro 3. -58 págs., Inf. Interno ICE.

BARQUERO, R. & ALVARADO, G.E., 1992: Los enjambres sísmicos en el arco volcánico de Costa Rica. -Bol. Obs. Vulcanológico Arenal, No 4: 18-30.

BARQUERO, R. & SOTO, G. 1992: Volcán Poás: Informe sismo-volcánico red portátil digital, periodo marzo-junio de 1991. –Inf. Interno ICE. 46 pp.

BAUMGARTNER, P.O., MORA, C.R., BUTTERLIN, J., SIGAL, J., GLACON, G., AZÉMA, J. & BOURGOIS, J., 1984. Sedimentación y paleogeografía del Cretácico y Cenozoico del litoral pacífico de Costa Rica. -Rev. Geol. Amér. Central, 1: 57-136.

BERGOEING, J.P., BRENES, L.G. & MALAVASSI, E., 1983: Geomorfología del Pacífico Norte de Costa Rica (explicación del mapa geomorfológico 1:100 000).- 110 pp. MOPT-IGN-UCR, San José.

BOMMER, J.J. & RODRÍGUEZ, C.E., 2002. Earthquake-induced landslides in Central América. -J. Eng. Geol., 63 (4): 89-220.

BORGIA, A., BURR, J., MONTERO, W., ALVARADO, G.E. & MORALES, L.D., 1990: Fault-propagation faults induced by gravitational failure and slumping of the Central Costa Rica Volcanic Range: Implications for large terrestrial and Martian volcanic edifices. - J. Geophys. Res., 89 (95): 14 357 - 14 382.

CARR, M.J., SAGINOR, I., ALVARADO, G.E., BOLGE, L.L., LINDSAY, F.N., MILIDAKIS, K., TURRIN, B.D.,

FEIGENSON, M.D. & SWISHER III, C.C., 2007: Element fluxes from the volcanic front of Nicaragua and Costa Rica. – Geochemistry Geophysics Geoystems, 8(6), 22 págs.

CARR, M., SAGINOR, I., ALVARADO, G.E., BOLGE, L.L., LINDSAY, F.N., MILIDAKIS, K., TURRIN, B.D.,

FEIGENSON, M.D., SWISHER, C.C., 2007: element fluxes from volcanic front of Nicaragua and Costa Rica. - Rev. Geochemistry, Geophysics, Geosystems. Vol. No. 8:6:1-22

CARRILLO, E., ET AL., 2002. *MAMÍFEROS DE COSTA RICA*. EDITORIAL INBIO. HEREDIA.

EL MENTOR COSTARRICENSE, 1846. *CAMINO AL NORTE*. P. 94.

CHINCHILLA, M., 2000: Estudio Mineralógico, Físico-Químico y Clasificación de los Suelos del Proyecto Hidroeléctrico Cariblanco (Alajuela, Costa Rica). -154 págs., Tesis de Licenciatura en Ingeniera Agronómica. Universidad Nacional. Heredia.

CIGOLINI, C., KUDO, A.M., BROOKINS, D.G. & WARD, D., 1991: The petrology of Poás Volcano lavas: basalt-andesite relationship and their petrogenesis within the magmatic arc of Costa Rica. – Journal of Volcanology and Geothermal Research, 48: 367-384.

CHOW, V.T., 1959. Open-Channel Hydraulics. -680 págs. New York, McGraw-Hill.

CLIMENT, Á., 1991. Algunos comentarios sobre la amenaza sísmica del P.H. Toro. -11 págs., Inf. Interno ICE, Depto. Geología.

CLIMENT, Á., ALVARADO, G.E. & BOSCHINI, I., 2006. P.H. Toro 3: Estudio de Amenaza Sísmica. -22 págs., Inf. Interno ICE.

CLIMENT, A. & ARROYO, I., 2002: P.H. Boruca, Estudio de Amenaza Sísmica. -Inf. Interno ICE. C.S.

Exploración Subterránea, PySA. 27 pp + figs.

CLIMENT, A., BARQUERO, R., & ALVARADO, G., 2002: Estimación de la Amenaza Sísmica del P.H.

Cariblanco. -Inf. Interno ICE. 11 pp.

CLIMENT, A., BARRANTES, J.M. Y PIEDRA, R., 2009. Registro de aceleraciones ICE, durante la ocurrencia del Terremoto del 8 de enero 2009. Informe Interno ICE. 7 pp.

CRONIN, S.J., NEALL, V.E., LECOINTRE, J.A. & PALMER, A.S., 1999. Dynamic interactions between lahars and stream flow: a case study from Ruapehu volcano, New Zealand. –Geol. Soc. Amer. Bull., 111: 28-38.

DENYER, P. MONTERO, W. & ALVARADO, G.E., 2003. Atlas tectónico de Costa Rica. -81 págs. Ed. Univ. Costa Rica, San José.

DEVOLI, G., DE BLASIO, F.V., ELVERHØI, A. & HØEG, K., 2009. Statistical Analysis of Landslide Events in Central America and Their Run-out Distance. -Geotech. Geol. Eng., 27: 23-42.

ELLEN, S. D. & FLEMING, R.W., 1987. Mobilization of debris flows from soil slips, San Francisco Bay region, California. -En: J.E. Costa & G. F. Wieczorek (eds): Debris flows/avalanches: Process, recognition, and mitigation. Geol. Soc. Amer. Review in Eng. Geology, VII: 31-40.

FERNÁNDEZ, A. más 19 co-autores (1997). Mapa Geológico de Costa Rica (1: 750 000). Ministerio del Ambiente y Energía.

FERNÁNDEZ, R., 2002. *COSTA RICA EN EL SIGLO XIX: ANTOLOGÍA DE VIAJEROS*. EDITORIAL UNIVERSIDAD ESTATAL A DISTANCIA. SAN JOSÉ.

GANS, P.B., MACMILLAN, I., ALVARADO, G., PÉREZ, W. & SIGARÁN, C., 2002: Neogene Evolution of the Costa Rican Arc. – Abstract, Geological Society of America 2002 Annual Meeting, Denver, October 2002.

GANS, P.B., ALVARADO, G., PÉREZ, W., MACMILLAN, I., & CALVERT, A., 2003: Neogene Evolution of the Costa Rican Arc and Development of the Cordillera Central. – Abstract, Geological Society of America, Cordilleran Section, 99th Annual, April 2003.

GARITA, F., 1997. *TOPONIMIA DE LA PROVINCIA DE HEREDIA*. EDITORIAL INSTITUTO GEOGRÁFICO NACIONAL. SAN JOSÉ.

GONZÁLEZ, P., 1976. *RUTA SARAPIQUÍ: HISTORIA SOCIOPOLÍTICA DE UN CAMINO*. INSTITUTO DE INVESTIGACIONES SOCIALES. UNIVERSIDAD DE COSTA RICA. SAN JOSÉ.

HALL, C., 1984. *COSTA RICA: UNA INTERPRETACIÓN GEOGRÁFICA CON PERSPECTIVA HISTÓRICA*. EDITORIAL COSTA RICA.SAN JOSÉ.

HILJE, L., 2009. *CINCHONA, DOLOR Y MEMORIA*. INFORMA-TICO, 16-I-2009. 3 P.

KEEFER, D. & WILSON, R., 1989. Predicting earthquakes-induced landslides with emphasis on arid and semiarid environments. -Publ. Inland Geol. Soc., 2: 118-149.

LAPORTE, G., 2009. Taludes y Sismos. Comportamiento dinámico de taludes durante el sismo de Cinchona y sus implicaciones al diseño geotécnico. -Bol. Geotécnico Notisuelos, 10: 6-7.

LAPORTE, M., BARQUERO, R. & CLIMENT, A., 1995: Estudio de Amenaza Sísmica para los P.H. Peñas Blancas, Laguna Hule y el P.G. Miravalles III. -Informe Interno ICE. OSV.95.17. 56 pp.

LIN, J. AND R.S. STEIN (2004), Stress triggering in thrust and subduction earthquakes, and stress interaction between the southern San Andreas and nearby thrust and strike-slip faults, J. Geophys. Res., 109, B02303, doi : 10.1029/2004JB002607.

LÓPEZ, A; 1999. Neo-and paleostress partitioning in the SW corner of the Caribbean plate and its fault reactivation potential. Ph.D dissertation, Tübingen Universität, 294 págs.

LÓPEZ, A; MARSHALL, J.S; CHINCHILLA, A.L; SAK, P.B; CHIESA, S; MESCHEDE, M; ALVARADO, G.E;

VILLEGAS, A; CALDERÓN, M; GAZEL. E; BARQUERO, R. 2008. Costa Rica Stress Map: the Sigma Project.

Poster IX Congreso Geológico de América Central y 3rd World Stress Map conference, GFZ, Potsdam, 2008.

MALAVASSI, E., 1991: Magma sources and crustal processes at the terminous of the Central American Volcanic Front. – xxii + 435 págs. Universidad de Santa Cruz, California [Tesis de PhD].

MARR, W., 2004. *VIAJE A CENTROAMÉRICA*. EDITORIAL DE LA UNIVERSIDAD DE COSTA RICA. SAN JOSÉ.MARR, W. ET AL., 1999. VIAJEROS POR EL SARAPIQUÍ: 1853-1859. MUSEO HISTÓRICO CULTURAL JUAN SANTAMARÍA. ALAJUELA.

MATUMOTO, T., OHTAKE., M., LATHAM, G. & UMAÑA, J. 1977: Crustal structure in Southern Costa Rica: San José Costa Rica, Instituto Costarricense de Electricidad, Dpto. de Geología, -Inf. Interno. 18 pp.

MELÉNDEZ, C., 1989. CARTOGRAFÍA HISTÓRICA DE COSTA RICA: SIGLOS XVI-XIX. JUNTA DE PROTECCIÓN

SOCIAL DE SAN JOSÉ Y COMISIÓN NACIONAL DEL QUINTO CENTENARIO DEL DESCUBRIMIENTO DE AMÉRICA. SAN JOSÉ.

MIYAMURA, S., 1980: Sismicidad de Costa Rica. -Ed. Universidad de Costa Rica. 190 pp.

MONTERO, W., 1994: Neotectonics and related stress distribution in a subduction-collisional zone: Costa Rica.- En:SEYFRIED, H. & HELLMANN, W. (eds.): Profil, 7: 125-141, Universität Stuttgart, Alemania.

MONTERO, W., 2001: Neotectónica de la región central de Costa Rica: frontera oeste de la microplaca de Panamá.- Rev. Geol. Amér. Central 24: 29-56.

MONTERO, W., DENYER, P., BARQUERO, R., ALVARADO, G.E., COWAN, H., MACHETTE, M.N., HALLER, K.M. &

DART, R.L., 1998: Map and Database of Quaternary Faults and Folds in Costa Rica and its Offshore Regions.-63 págs. (+1 mapa). U.S. Geol. Survey, International Lithosphere Program, Major Active Faults of the World, Colorado [Inf. preliminar 98-481].

MOLINA, C., 2005. *Y LAS MULAS NO DURMIERON … LOS ARRIEROS EN COSTA RICA. SIGLOS XVI AL XIX*. EDITORIAL UNIVERSIDAD ESTATAL A DISTANCIA. SAN JOSÉ.

MORA, S. & MORALES, L.D., 1986. Los sismos como fuente generadora de deslizamientos y su influencia sobre la infraestructura y líneas vitales de Costa Rica. –Memoria 4º Seminario Latinoamericano de Ingeniería Sísmica, San José, pp. 201-214.

MORA, R. & MORALES, L.D., 1992. La susceptibilidad a la inestabilidad de laderas en la zona norte de Alajuela y el terremoto de Fraijanes de 1888. Efectos y previsión. -Rev. Geográf. Amér. Central, 25-26: 311-322. MORA, S. & MORA, R., 1994. Los deslizamientos causados por el terremoto de Limón: Factores de control y comparación con otros eventos en Costa Rica. -Rev. Geol. Amér. Central, vol. Especial Terremoto de Limón, 139-152 pp.

MORALES, L.D. 1985: Las zonas sísmicas de Costa Rica y alrededores. -Rev. Geol. Amér. Central. 3:69-101

LAPORTE, M., BARQUERO, R. & CLIMENT, A., 1995: Estudio de Amenaza Sísmica para los P.H. Peñas Blancas, Laguna Hule y el P.G. Miravalles III. -Informe Interno ICE. OSV.95.17. 56 pp.

MOYA, A., SCHMIDT, V., ROJAS, V., SEGURA, C., CORDERO, E. Y SANOU, O., 2009. Informe preliminar del registro de aceleraciones del sismo del 08 de enero del 2009. LIS-IINI-UCR. 6 pp.

NOSTRO, C, R.S. STEIN, M. COCO, M.E. BELARDINELLI & W. MARZOCCHI, 1998: Two-way coupling between Vesuvius eruptions and southern Apennine earthquakes (Italy) by elastic stress transfer. J.G.R., 103, pp. 24.487-24.504.

OBREGÓN, C., 1968. LA ADMINISTRACIÓN DEL DOCTOR CASTRO 1847-1849. SEGUNDO TOMO: POLÍTICA EXTERNA. TESIS DE LICENCIATURA. UNIVERSIDAD DE COSTA RICA. SAN JOSÉ.

OKADA, Y; 1992. Internal deformation due to shear and tensile faults in a half-space. BSSA, 82, 1018- 1040.

PENNING-ROWELL, E.C., TUNSTALL, S.M., TAPSELL, S.M. & PARKER, D.J., 2000. The Benefits of FloodWarning: Red but Elusive, and Politically Significant. -J. Inst. Water and Environm. Man., 14: 7-14.

PERALDO, G. & MONTERO, W. 1999: Sismología histórica de América Central. -Ed. IPGH. 347 pp.

PÉREZ, W., ALVARADO, G.E. & GANS, P.B., 2006: The 322 ka Tiribí Tuff: Stratigraphy, geochronology and mechanisms of deposition of the largest and most recent ignimbrite in the Valle Central, Costa Rica. – Bulletin of Volcanology, 69: 25-40.

PIERSON, T.C., 1995. Flow characteristics of large eruption-triggered debris flows at snow-clad

volcanoes: constraints for debris-flow models. -J. Volcanol. Geotherm. Res., 66: 283-294.

PIERSON, T.C., JANDA, R.J., THOURET, J.C. & BORRERO, C.A., 1990. Perturbation and meeting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Colombia, and consequent mobilization, flow, and deposition of lahars. -J. Volcanol. Geotherm. Res., 41: 17-66.

PROSSER, J. & CARR, M., 1987. Poás volcano, Costa Rica: Geology of the summit region and spatial and temporal variations among the most recent lavas. J. Volcanol. Geotherm. Res., 33: 131-146.

RED SISMOLÓGICA NACIONAL: -Bol. De la Red Sismológica Nacional.

RODRÍGUEZ, C.E., 2002. Earthquake-induced landslide. -En: J. Bundschuh & G.E. Alvarado (eds.): Central America: Geology, Resources and Hazards. Taylor & Francis, Londres, 2: 1217-1255.

ROJAS, L., 1993: Estudio geológico-geotécnico de reconocimiento de un sector del Proyecto

Hidroeléctrico Laguna Hule.- 42 págs. (+ 2 apén. y 3 mapas). Univ. de Costa Rica, San José [Inf. Campaña Geol.].

SANDOVAL, L.F. & 11 co-autores (1982). Mapa Geológico de Costa Rica (1: 200 000). -Ed. Dirección de Geología, Minas y Petróleo, Min. De Industria, Energía y Minas.

SAPPER, K. 1925: Los volcanes de la América Central. (Libro del mes: 46 pp.). Halle (Saale), Max Niemeyer Vrlag, 144 pp.

SCOTT, K.M., 1988a. Origins, behavior, and sedimentology of lahars and lahar-runout flows in the Toutle-Cowlitz River system. -74 págs. U.S. Geological Surv. Prof. Paper 1447-A.

SCOTT, K.M., 1988b. Origins, behavior, and sedimentology of prehistoric catastrophic lahars at Mount St. Helens, Washington. -En: Clifton, H.E. (ed.): Sedimentology consequences of convulsive geologic events: Geol. Soc. Amer. Spec. Paper 229: 23-36.

SIMONS, D.B. & RICHARDSON, E.V., 1963. Resistance to flow in alluvial channels. -59 págs., U.S. Geol. Surv. Professional Paper 422J.

SMITH, G.A. & Fritz, W.J., 1989. Volcanic influences on terrestrial sedimentation. -Geology, 17: 375-376.

SOTO, G.J., 1999: Geología regional de la hoja Poás (1:50 000).- En: ALVARADO, G.E. MADRIGAL, L.A.. (eds.): Estudio geológico-geotécnico de avance de factibilidad del P.H. Laguna Hule.- 113 págs. (+ anexo). – Inf. Interno, Centros Servicio Diseño y Exploración Subterránea, ICE.

SOTO, G.J. & ARREDONDO, S.G., 2007: Chronostratigraphic summary of Barva Formation (Costa Rica). – Abstract volume, Workshop to Integrate Subduction Factory and Seismogenic Zone Studies in Central America, junio 18-22, 2007, Heredia, Costa Rica, p. 103 (en cibersitio http://www.nsfmargins. org/CostaRica2007/index.html).

SOTO, G.J., 1990. Consideraciones volcanológicas y tectónicas preliminares del área de Laguna Hule. – Sección de Sismología e Ingeniería Sísmica, ICE, 14 págs.

SOTO, G.J., 1994: Volcanología Física. – En: DENYER, P. & KUSSMAUL, S. (comps.): Atlas Geológico Gran Área Metropolitana. – Editorial Tecnológica de Costa Rica: 131-146.

SOTO, G.J., 1999: Geología regional de la Hoja Poás. – En: ALVARADO, G.E. & MADRIGAL, L.A. (eds.):

Estudio geológico-geotécnico de avance a la factibilidad del P.H. Laguna Hule. –Informe interno

Instituto Costarricense de Electricidad, San José, págs. 15-45 + mapa geológico escala 1:50 000.

SOTO, G.J., PÉREZ, W. & ARREDONDO, S.G., 2008: ¿Cuán extensa y voluminosa es la Formación Tiribí, Costa Rica? Nuevos hallazgos y reinterpretaciones. – Memoria: Programa y Resúmenes, IX CongresoGeológico de América Central y VI Congreso Geológico Nacional, 2-4 de julio del 2008, San José, Costa Rica, p. 184-185.

TODA, S., R.S. STEIN, K. RICHARDS-DINGER AND S. BOZKUT, 2005: Forecasting the evolution of seismicity in southern California: Animations built on earthquakes stress transfer, J. Geophys. Res., B05S16, doi : 10.29/2004JB003415.

TOURNON, J., 1984: Magmatismes du Mesozoique a l'actuel en Amérique Centrale: l'exemple de Costa Rica, des ophiolites aux andésites. – Mémoire des Sciences de Terre, Université Pierre et Marie Curie, París, 84-49, 335 págs ISTÁN, J.P., BIOLEY, P. & COTS, C. 1912: The Sarchí Earthquake, Costa Rica. -Bull. Seismol. Soc. Amer. V.2:201-208.

VON FRANTIUZ, A., 1861. Beiträge zur Kenntniss der Vulkane Costa Ricas. Petermann's Geographische Mittheilungen. Helt IX y Helt X, Gotha: Justus Perthes, 381-385 pp.

VON FRANTZIUS, A., 1999. *LA RIBERA DERECHA DEL RÍO SAN JUAN: UNA PARTE CASI DESCONOCIDA DE COSTA RICA*.MUSEO HISTÓRICO CULTURAL JUAN SANTAMARÍA. ALAJUELA.

WIELAND, M. & MUELLER, R., 2009. Dam safety, emergency action plans and water alarm systems. -Int. Water & Dam Construction, Enero, www.waterpowermagazine.com, 34-38.

WILFORD, D.J. & SCHWAB, J.W., 1982. Soil mass movements in the Rennell Sound area, Queen Charlotte Islands, British Columbia. -En: Proceeding of the Canadian Hydrology Symposium, 521-541.

ZOBIN, V.M., PLASCENCIA, I., REYES, G. & NAVARRO, C., 2008. The characteristics of seismic signals produced by lahars and pyroclastic flows: Volcán de Colima, México. -J. Volcanol. Geotherm. Res., 179: 157-167. doi: 10.1016/j.jvolgeores.2008.11.001.