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Site investigation, monitoring and stability analysis of a built-up slope involved by gas pipeline explosion

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ABSTRACT: The paper describes the results of site investigations, monitoring and stability analyses of a build-up slope located near Pineto (Italy). In March 2015 the explosion of a gas pipeline in the upper portion of the slope caused extensive damage to existing buildings and lifelines. Soon after the event, a site investigation and monitoring program was planned. The site investigation included 3 boreholes (25-30 m depth) and 3 flat dilatometer tests DMT (15 to 30 m depth) carried out inside the boreholes by use of the "torpedo" system. The boreholes were instrumented for inclinometer and piezometer measurements. A detailed topographic survey was carried out to reconstruct the ground profile. Hydrological data were analysed for possible critical rainfall events. The slope is formed by OC clay, covered with an upper, 10-14 m thick clayey-sandy silt colluvial layer. The stability of the slope was analysed both in pre- and in post-explosion conditions. The pre-explosion conditions were back-analysed assuming different levels of the groundwater table (at the time of the explosion presumably close to the ground surface). The analyses, in agreement with field observations, indicated that the slope is unstable and possibly slope movements may have been one concurrent cause of failure of the pipeline. The profiles of the DMT horizontal stress index K_D helped identify multiple slip surfaces.

1 INTRODUCTION

When a buried pipeline is installed within an unstable slope in which large-scale ground movements might occur, these movements may induce substantial axial/bending strains and stresses in the pipeline, with possible risk of rupture. The methods to predict landslide-induced pipeline strains and stresses are not well described in design standards or codes of practice. Finite element analysis of soil-pipe interaction is potentially an effective tool to model the pipeline response to slope movements. All the above significant engineering issues have received particular attention in recent studies (for instance Hodder & Cassidy 2010, Lin et al. 2011, Zhang & Duan 2012, Zhou 2012, Contreras et al. 2013, Fredj & Dinovitzer 2014, Ho et al. 2014, Petro et al. 2014, Sahdi et al. 2014, Auflič et al. 2015, Fredj et al. 2015).

On March 6, 2015 the explosion of a gas pipeline in the upper portion of the slope of Colle Cretone (Pineto, Italy) caused extensive damage to existing buildings and lifelines. The explosion triggered a fire of gigantic proportions. The heat of the fire damaged the existing buildings, as well as trees and overhead power lines, in a radius of more than 200 m from the breaking point. A landslide occurred over an interval of about 1-2 hours with a speed of about 20-40 cm/hour, leaving numerous cracks on the ground surface and generating displacements/rotations on the retaining walls nearby.

This paper describes the results of the site investigation, the monitoring program and the stability analyses of the slope carried out in the months following the gas pipeline explosion. The analyses, in agreement with field observations, indicated that the slope movements have been one concurrent cause of failure of the pipeline. Geotechnical analyses revealed that the movements along the slope had a direction almost collinear with the longitudinal axis of the damaged pipeline. The information presented in this paper is the basis for further analysis of the mechanical behaviour of the pipeline interacting with the slope movement and evaluation of the pipeline strain demand.

2 GEOLOGICAL AND GEOMORPHOLOGICAL SETTING OF COLLE CRETONE SLOPE

The hillside area of Colle Cretone (Pineto, Italy) is composed of a Middle-Upper Pliocene grey-blue clay formation, whose top surface gently dips toward the Adriatic sea. Above these formation colluvial silty-clayey-sandy deposits, which reflect an intense recent evolutionary phase, are encountered. Due to their widespread areal diffusion and significant thickness, which may exceed 10 m, the colluvial deposits can be regarded as a real geological formation.

The hills are shaped by the presence of ditches and small streams which flow into the major rivers in the Abruzzo region. The sides of the valleys excavated by these streams show a markedly asymmetrical profile. The side of the valley that slopes more gently is modelled in the colluvial deposits. Its morphology indicates the presence of slow movements in progress (about 15-20 mm/year). The only surficial evidence of such slow movements has the form of ground surface undulations. Ditches are in rapid erosion and make the slopes of the valley continuously steeper, which is the origin of the slow slope movements. Generally movements are reactivated in correspondence of continuous rainfall, while they cease completely in the dry periods.

Slow slope movements are not among the landslides that more directly recall the image of "catastrophe", intended as a phenomenon (more or less unexpected, or unforeseen) that produces substantial damage in a short time, even though it may be characterised by different stages (Leroueil 2001). Nevertheless slow movements are particularly insidious, due to their widespread diffusion and low surficial evidence. They typically affect gently sloping areas, usually selected for siting of settlements and infrastructures that are destined, sooner or later depending on the precautions that have been taken, to suffer (at times irreparable) damage during the evolution of the movement.

As noted above, in this area slow slope movements have a seasonal character, directly related with variations of the ground water level induced by rainfall. Based on the results of monitoring continued for over 10 years on similar slopes, the position of the slip surface generally lies within, and/or at the base, of an upper debris layer, at the contact between this layer and the weathered/softened portion of the base clay formation, or sometimes deeper, within the base clay formation.

As featured in various maps, including regional ones, the area of Colle Cretone has long been affected by slow movements. Figure 1 shows the area of reactivation/expansion of the movement which occurred on March 6, 2015, involving the gas pipeline. Figure 1 also shows an excerpt from a planimetric map retrieved from official cartography of the Abruzzo regional authority, dating back nearly 20 years ago.

Figure 2 shows a schematic section of the water flow system that affects the slope from Colle Cretone (Cretone Hill) towards the Cerrano stream at its toe. In this context, the continuous influx of stormwater promotes saturation/imbibition of the colluvial cover, causing a reduction of shear strength and thus giving rise to the reactivation of the movement.

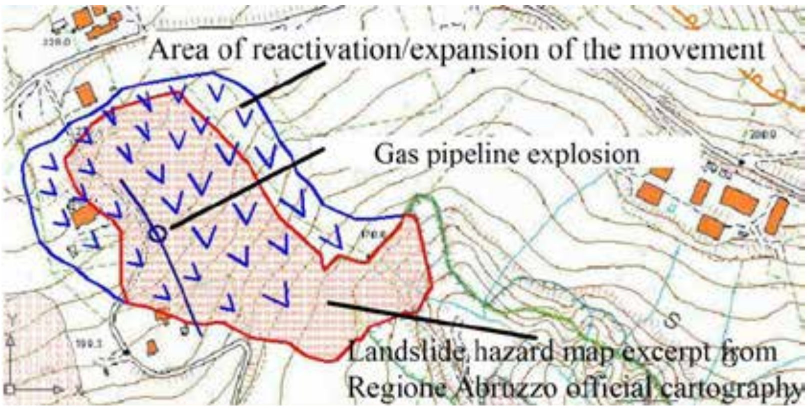

Figure 1. Area of reactivation/expansion of the movement occurred on March 6, 2015, involving the gas pipeline.

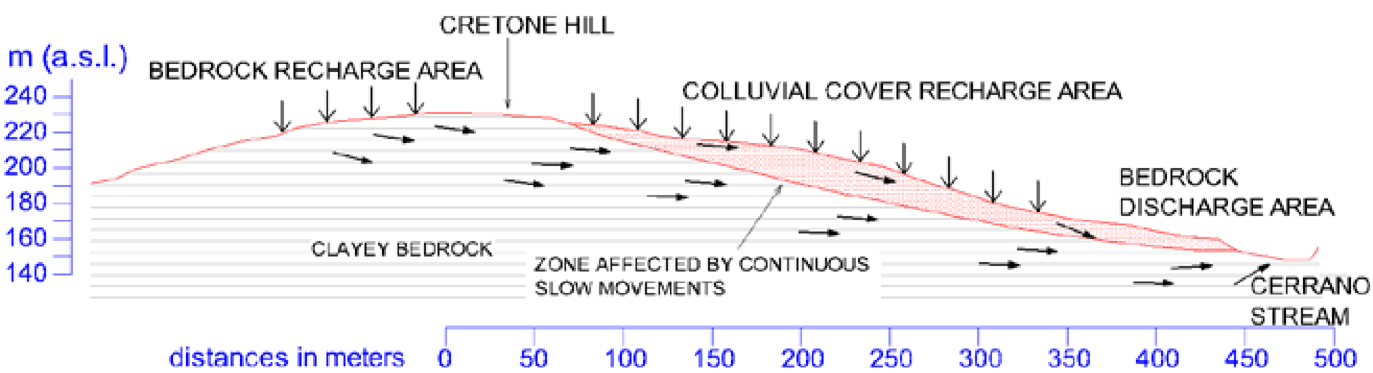

Figure 2. Schematic section of the water flow system across the slope.

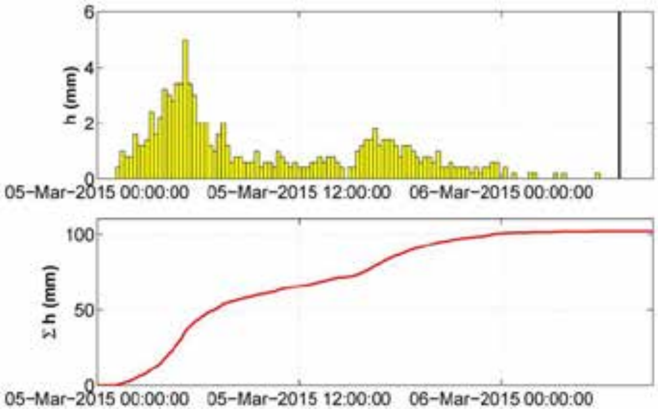

Figure 3. Height of rain recorded by pluviograph (March 5-6, 2015 event).

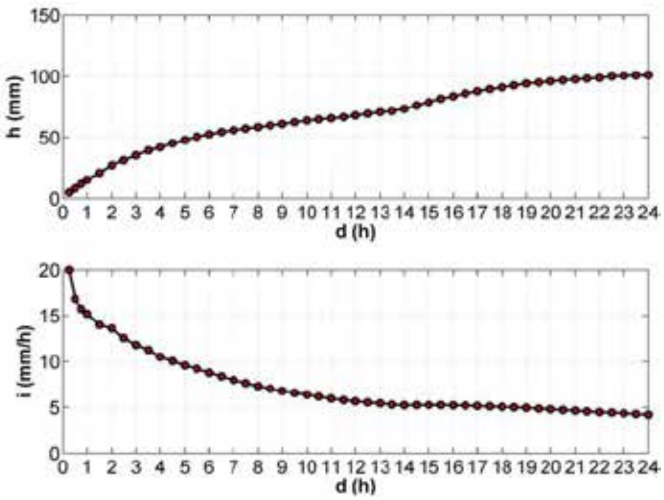

Figure 4. Height of rain cumulated during the March 5-6, 2015 event.

3 RAINFALL EVENTS OF FEBRUARY-MARCH 2015

During February-March 2015 the slope was subjected to particularly intense “rainfall paths”. Following are the results of the analysis of the rain event happened on March 5 and 6, 2015. This analysis has permitted to evaluate the characteristics of the event in terms of duration and intensity, as well as the associated return period.

Figure 3 shows the values of the height of rain recorded by pluviograph. Figure 4 reports the height of rain cumulated during the event. The analysis of the data indicates that the event began on the night of March 5 (01:30 UTC) and lasted continuously until late in the evening (23:45 UTC), with a total height of rain of 102 mm. Peak intensity occurred at 5:15 UTC, in the first stage of the event, reaching the value of 20 mm/hour.

The analysis of rainfall data before the event of March 5 has shown the prior occurrence of two events lasting more than 20 hours, respectively on February 6-7 and on February 25-26. The total height of rain for this last event (occurred seven days before the event in question) was 97 mm.

4 SITE INVESTIGATION AND MONITORING

A site investigation and monitoring program was planned soon after the pipeline explosion (Figure 5).

Three boreholes were drilled along the slope to 25-30 m depth, in order to obtain detailed stratigraphic information. Flat dilatometer tests (DMT) were carried out inside the boreholes by use of the “torpedo” system to 15-30 m depth.

The DMT tests were aimed at identifying the slip surfaces involved by the expansion/retrogression of the landslide occurred on March 6, 2015, based on the method proposed by Totani et al. (1997). This method permits to detect quickly active/past slip surfaces in overconsolidated (OC) clay slopes, based on the inspection of the profiles of the DMT horizontal stress index K_D (Marchetti 1980). The method is based on the following two assumptions:

(a) The sequence of sliding-remoulding creates a remoulded zone of nearly normally consolidated (NC) clay, with loss of structure, aging, cementation.

(b) Since in NC clays $K_D \approx 2$, if an OC clay slope contains layers where $K_D \approx 2$, these layers are likely to be part of a slip surface (active or quiescent).

In essence, the method consists in identifying zones of NC clay in a slope which, otherwise, exhibits an OC profile, using $K_D \approx 2$ as the identifier of the NC zones (see also Marchetti et al. 2001).

The three borehole logs (Figure 6) show that the upper colluvial silty-clayey-sandy deposit has a thickness varying between 11 m (at the topmost borehole location) and 14 m (at lower elevation).

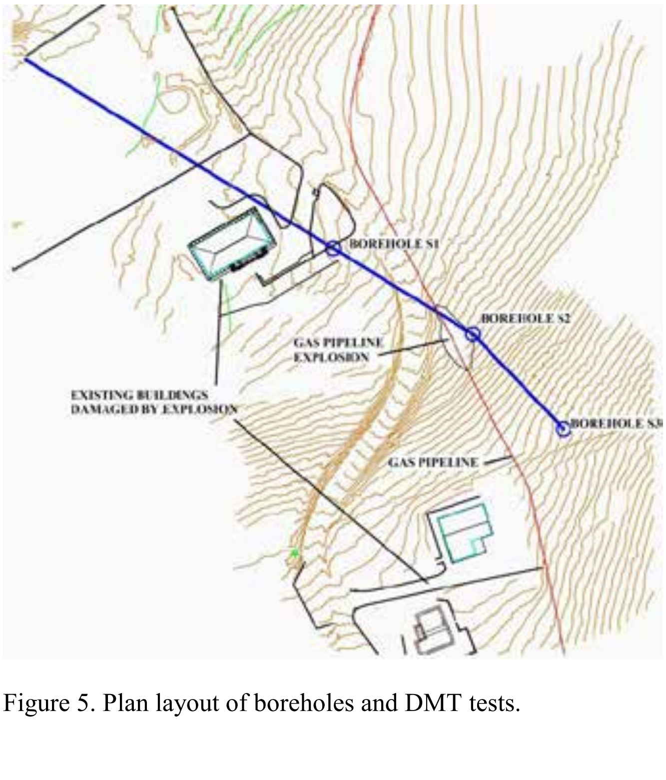

Figure 5. Plan layout of boreholes and DMT tests.

The base blue clays are found about 14 m below the ground surface, with a top surface dipping down toward the valley.

Significant evidence regarding the thickness of soil above the pipeline involved by the landslide is provided by the K_D profile from DMT 1. The section in Figure 6 shows that, above the pipeline, the soil is quite altered/remoulded to a depth of approximately 7.6 m, with a minimum peak of $K_D \approx 2$ just at that depth. Based on this information and taking into account the location of cracks and fissures on the surface, it was possible to reconstruct the geometry of the landslide mobilised by the rainfall event of March 5-6, 2015.

The inspection of the K_D profiles from DMT 2 and DMT 3 (Figure 6 and Figure 7, top) does not reveal any zones with $K_D \approx 2$ or recently remoulded soil layers. Hence it can be concluded that a "neo-formation" roto-translational landslide was triggered on March 6, 2015, involving the portion of slope above the pipeline. The investigation then confirms the geomorphological interpretation, which indicates an extension due to retrogression of a pre-existing slow slope movement.

Figure 7 shows the profiles of the constrained modulus M and of the undrained shear strength c_u obtained from DMT 1. It can be noticed that the landslide, by remoulding the soil, has produced a substantial deterioration of the mechanical properties in the upper 7-7.5 m.

Inclinometer casings and Casagrande piezometers were installed in the three boreholes, in order to monitor the landslide movements and the pore pressures. Inclinometer and piezometer measurements are in progress. A detailed topographic survey was also carried out to reconstruct the ground profile along the slope.

Direct shear tests, with measurement of the residual shear strength after several reversal cycles, were executed on samples retrieved from the colluvial, soft to stiff (when dry) clayey-silty-sandy layer. Figure 8 (left) shows typical shear strength vs. horizontal displacement curves. The interpreted shear strength values are shown in Figure 8 (right). The relatively high values of the residual friction angle of the soil may depend on the scarce activity of the clay minerals.

5 STABILITY ANALYSES

The stability of the slope in the zone of the landslide occurred on March 6, 2015 was back-analysed assuming two different ground water conditions (Figure 9): (1) ground water table at ground surface; (2) ground water table from about 3 to 6 m below ground surface.

If the peak shear strength is assumed in the colluvial cover, the safety factor (Fs) variations are scarcely influenced by changes in pore water pressures. If one refers to the residual shear strength, the values of Fs vary from 0.95 to 1.05. Such values may explain well the movement of the colluvial cover.

The fact that the equilibrium of the slope is governed by the residual strength implies the presence of a pre-existing slip surface, or at least of a soil band of narrow thickness, whose strength was reduced nearly to the residual value due to large or long lasting deformations.

This latter condition is in agreement with the morphological evolution of the slope, that suggests the permanence of the present conditions for a long time.

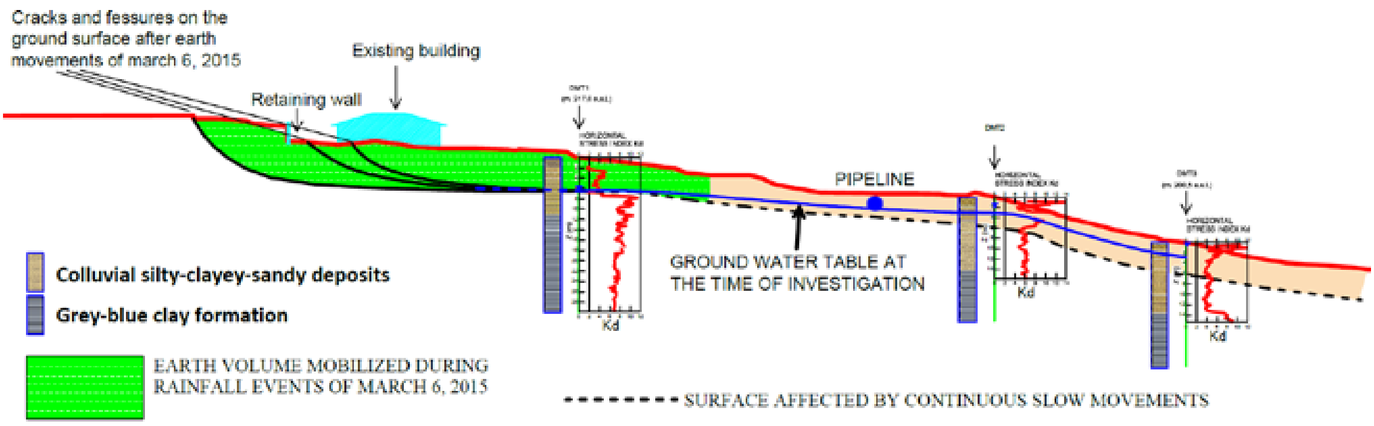

Figure 6. Longitudinal section of the slope and results of site investigation (boreholes and flat dilatometer tests).

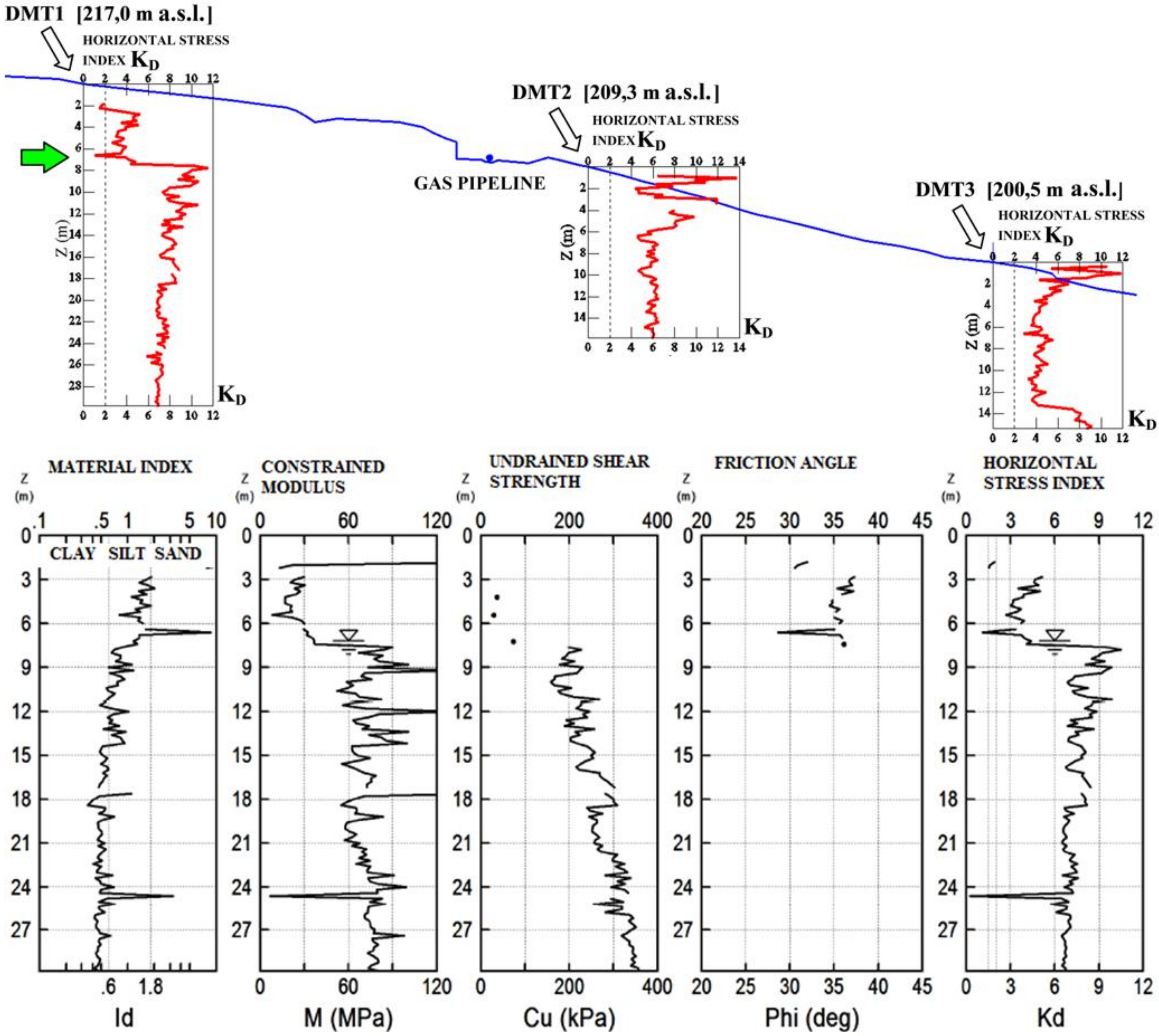

Figure 7. Profiles of K_D from all DMTs (top) and parameters interpreted from DMT 1 (bottom).

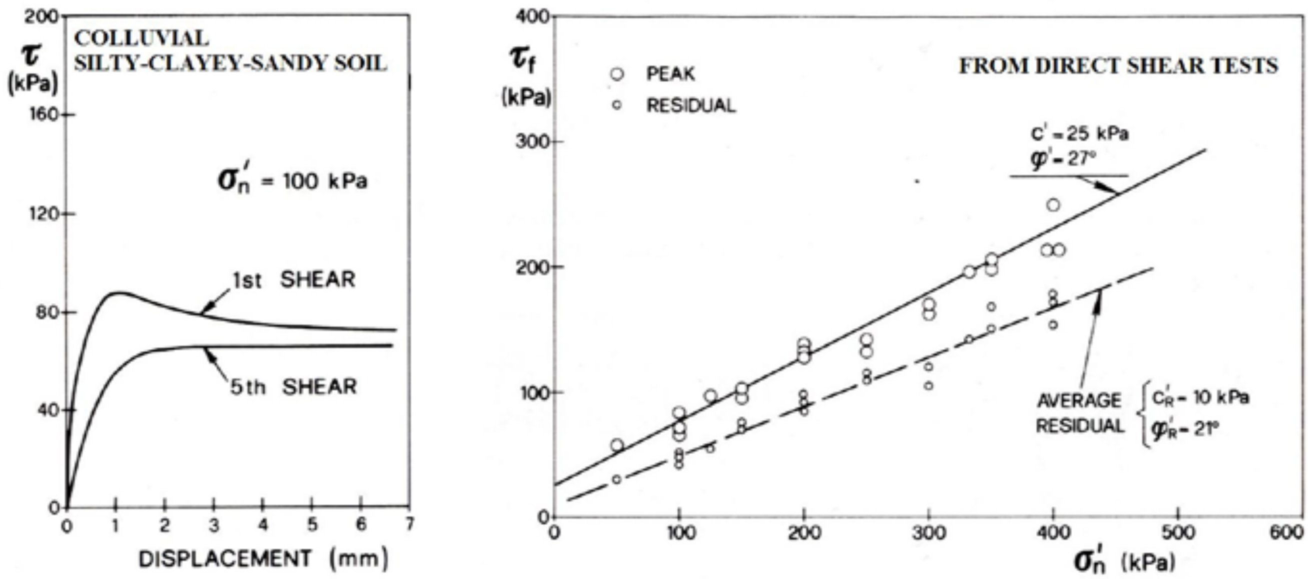

Figure 8. Results of direct shear test on a sample retrieved in borehole S1 (depth 6.00 m).

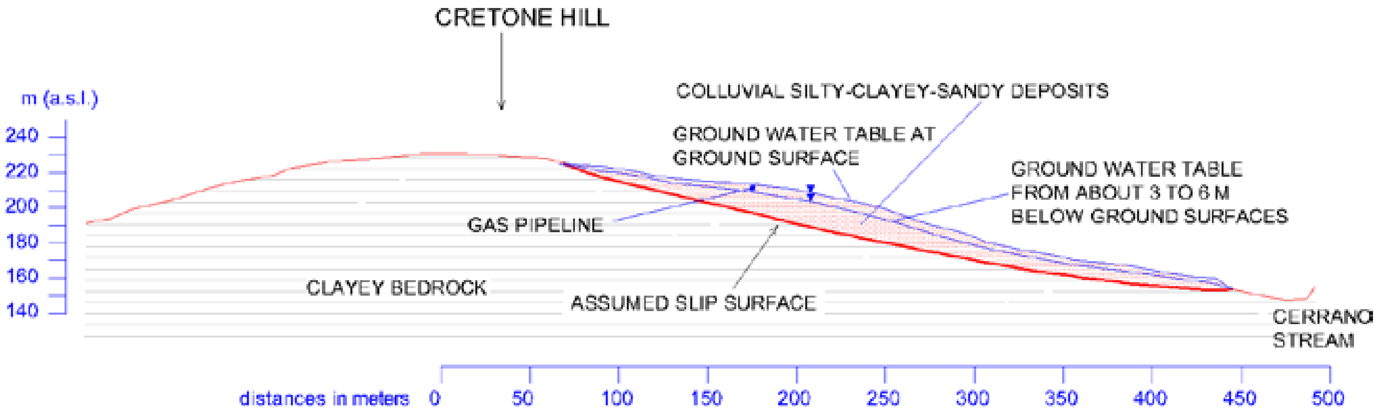

Figure 9. Slip surface and ground water conditions assumed in the back-analysis.

6 CONCLUDING REMARKS

The analysis illustrated in this paper indicates a possible relation between the rupture of the buried gas pipeline and slope movements.

The shallow colluvial cover, in which the pipeline is located, could be affected by continuous slow movements, governed by the pore water pressure regime.

The equilibrium conditions of the slope are controlled by shear strength near to the residual strength in a softened band within the colluvial cover and by pore water pressure variations in the same layer.

As a general conclusion, it can be said that exceptional climatic conditions may influence the equilibrium conditions of such colluvial covers.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

Auflič, M.J., Komac, M. & Šinigoj, J. 2015. Modern remote sensing techniques for monitoring pipeline displacements in relation to landslides and other slope mass movements. *Environmental Security of the European Cross-Border Energy Supply Infrastructure,* 31-48.

Contreras, M.F., Vergara, C., Pereira, M., Colonia, J.D. & García, H. 2013. Pipeline integrity assessment and mitigation techniques in unstable soil conditions based on comparison of in line inspection results. *Proc. 1st ASME International Pipeline Geotechnical Conference, Bogota, Colombia*.

Fredj, A. & Dinovitzer, A. 2014. Pipeline response to slope movement and evaluation of pipeline strain demand. *Proc. 10th International Pipeline Conference, Calgary, Alberta, Canada,* 4, doi: 10.1115/IPC2014-33611.

Fredj, A., Dinovitzer, A. & Sen, M. 2015. Application of the SPH Finite Element Method to evaluate pipeline response to slope instability and landslides. *Proc. 10th European LS-DYNA Conference, Würzburg, Germany*.

Ho, D., Wilbourn, N., Vega, A. & Tache, J. 2014. Safeguarding a buried pipeline in a landslide region. *Proc. Pipelines 2014: From Underground to the Forefront of Innovation and Sustainability, Portland, Oregon, USA,* 1162-1174, doi: 10.1061/9780784413692.105.

Hodder, M.S. & Cassidy, M.J. 2010. A plasticity model for predicting the vertical and lateral behaviour of pipelines in clay. *Géotechnique,* 60(4): 247-263.

Leroueil, S. 2001. Natural slopes and cuts: movement and failure mechanisms. *Géotechnique,* 51(3): 197-243.

Lin, D., Lei, Y., Xu, K., Huang, R., Luo, M. & Tao, H. 2011. An experiment on the effect of a transverse landslide on pipelines. *Acta Petrolei Sinica,* 32(4): 728-732.

Marchetti, S. 1980. In Situ Tests by Flat Dilatometer. *J. Geotech. Engrg. Div.,* 106(GT3): 299-321.

Marchetti, S., Monaco, P., Totani, G. & Calabrese, M. 2001. The Flat Dilatometer Test (DMT) in Soil Investigations – A Report by the ISSMGE Committee TC16. Official version approved by TC16 reprinted in *Flat Dilatometer Testing, Proc. 2nd Int. Conf. on the Flat Dilatometer, Washington D.C., USA,* 2006, Failmezger R.A. & Anderson J.B. (eds), 7-48.

Petro, L., Jánová, V., Žilka, A., Ondrejka, P., Liščák, P. & Balík, D. 2014. Catastrophic landslide in Nižná Myšla village (eastern Slovakia). *Landslide Science for a Safer Geoenvironment, Volume 3: Targeted Landslides,* 305-311.

Sahdi, F., Gaudin, C., White, D.J., Boylan, N. & Randolph, M.F. 2014. Centrifuge modelling of active slide-pipeline loading in soft clay. *Géotechnique,* 64(1): 16-27.

Totani, G., Calabrese, M., Marchetti, S. & Monaco, P. 1997. Use of in-situ flat dilatometer (DMT) for ground characterization in the stability analysis of slopes. *Proc. XIV ICSMFE, Hamburg, Germany,* 1: 607-610.

Zhang, P. & Duan, Y. 2012. Study on failure probability model of LanChengYu pipeline under landslide geological disaster. *Information, Special Issue on Reliability, Maintenance, and Safety Engineering: Recent Progress in China,* 15(12B): 5683-5692.

Zhou, W. 2012. Reliability of pressurised pipelines subjected to longitudinal ground movement. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance,* 8(12), doi: 10.1080/15732479.2010.505244.