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GEOPHYSICAL IMAGING OF LANDSLIDES IN VARIOUS GEOLOGICAL SETTINGS

GEOFYZIKÁLNÍ PRŮZKUM SESUVŮ V RŮZNÝCH GEOLOGICKÝCH PROSTŘEDÍCH

Master thesis

Supervisor: Mgr. Jan Valenta, Ph.D.

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Abstrakt

Pro zjištění detailní stavby těla sesuvů v okolí města Mekele v severní Etiopii bylo, jakožto součást většího objemu geologických prací, provedeno měření pomocí mělké refrakční seismiky. Zájmová oblast je hornatá s hluboce zaříznutými údolími s prudkými svahy, do kterých je zaříznuta hlavní silnice spojující města na severu Etiopie s hlavním městem, Addis Abebou. Sesuvy jsou zde jedním z hlavních inženýrsko-geologických problémů. Především během období dešťů způsobují značné škody nejen na infrastruktuře oblasti, ale i na polích a plodinách. Hlavním cílem prací bylo zjistit geotechnické parametry geologického prostředí a stanovit konkrétní příčiny vzniku sesuvů. Získané informace budou použity pro územní plán rozvoje oblasti. Dalším z cílů prací je je získat informace o potenciálním výskytu stavebních surovin a případných dalších geohazardů ohrožujících stávající či plánované stavby.

Výsledky měření ukazují, že tělesa sesuvů jsou tvořena materiálem s velmi nízkými hodnotami rychlostí P-vln (nesoudržný, nekonsolidovaný materiál). Podloží sesuvů tvoří pevné sedimenty charakterizované zvýšenými (relativně) hodnotami rychlostí šíření P-vln. Povedlo se identifikovat geometrii sesuvů a zjistit mocnosti nestabilních sedimentů. Zjistilo se, že akumulovaný materiál na úpatí skal, ve kterém je vedeno těleso silnice, je tvořen nezpevněnými sedimenty. Nestabilitu svahů dále zvyšuje hlavní silnice přitěžující svrchní části sesuvů. Pokud jsou svahy přitíženy dodatečnými stavbami (zvýšení zatížení svahu) či snížením únosnosti materiálu tvořícího svah (například zářezem či zvýšením obsahu vody) doposud stabilní svah se stane nestabilním.

Abstract

A geophysical survey using the seismic refraction tomography(SRT) was carried out to study a landslide areas in Mekele, Northern Ethiopia as a part of large investigation. The study area is characterized by steep topography and a road cut of Addis Ababa-Tigray main road which has a high economic benefit for the country. In the study areas landslides are one of the most frequent geo-hazard phenomena. They are frequently damaging the road as well as the farming land, mainly during the rainy seasons. The main objective of this investigation is to produce explanatory report providing information about geotechnical properties of rocks and soils and the cause of landslides in the area. The information is utilized for planning a land use and for various kinds of engineering constructions. In addition, the obtained data and

interpretation models provides information about construction material resources, identification and remediation of another geo-hazards with impact on the location, design and construction of engineering structures, and selection of potential sites for the ongoing constructions. The landslide material was characterized by a low seismic velocity. A layer of consolidated clastic rocks are considered to be the landslide bedrock and it is represented by a relatively high velocity. The results of the refraction survey identified the geometry of the failure surface and the changes in thickness of landslide materials. The accumulated material at the foot of the slopes is an unconsolidated material. The main road going through the landslide causes load on the crown of the landslide and results in slope instability. When stability conditions of the slope are disturbed either by the increase of stress imposed on the slope and / or by the decrease in strength of the earth material building up the slope and it involves enmass downward movement of earth material under the influence of gravity so that the materials could move easily.

Prohlášení/ Declaration

Prohlašuji, že jsem závěrečnou práci zpracoval samostatně a že jsem uvedl všechny použité informační zdroje a literaturu. Tato práce ani její podstatná část nebyla předložena k získání jiného nebo stejného akademického titulu.

I declare that I carried out this master thesis independently, and only with the cited sources, literature and other professional sources.

In Prague, 16.8.2019

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Ezra Haile Tadesse

1.Introduction

Cities in the developing countries face many problems related with a high urbanization rate. Growing populations are limited in their geographic expansion, by unstable, steep, or remote areas. Often, stabilizing landslide-scarred areas is too costly, and some inhabitants have no other places to relocate. Due to the fact that different problems such as an unplanned settlement, inadequate infrastructures, unofficial and illegal waste disposal sites, etc these outdated land-use policies may not always make the best planning for use of land that is vulnerable to landslides (Göktürkler, G., Balkaya, Ç., & Erhan, Z. (2008). The reasons for poor or nonexistent land-use policies that minimize the perceived or actual danger and damage potential from geologic hazards are many and encompass the political, cultural, and financial complexities and intricacies of communities (Highland & Bobrowsky, 2008). Landslides often are characterized as local problems, but their effects and costs frequently cross local jurisdictions and may become State or Provincial or national problems. As with many natural disasters, the effects of landslides are disproportionately severe in developing countries. This difference reflects a number of factors, including the resilience of basic infrastructure and emergency services; the availability of health care to treat people who are injured or left homeless; and patterns of development that determine where people live. Improving basic economic conditions and construction standards in high-risk areas could go a long way toward mitigating losses from landslides. Another major difference is that developing countries have no early warning systems that can alert people to imminent risks. High urbanization rate and unplanned settlement in a city may put life at risk in terms of natural hazard and nowadays many cities in the world are under such risk (Conversation media group, 2019).

Landslides are environmental processes that lead to natural disasters or technical failures, the effects of which usually threaten the life, health, property of people and infrastructures of the country (Highland & Bobrowsky, 2008). The road in the locality is impacted by landslides,which occur most frequently as deep seated land slide failures in the road cuttings. It causes temporary partial block of the traffic flow.It also requires a major road repair every season.The term landslide refers to a large variety of mass movements ranging from very slow slides in soils to rock avalanches. Several landslide classifications were proposed and the most widely used at the present time is probably the one of Cruden and Varnes (1996) which mainly considers the activity (state, distribution, style) and the description of movement (rate, water content, material type). Landslides affect all geological materials and exhibit a large variety of shapes and volumes.The characterisation of these phenomena is not a straightforward problem and may require a large volume of investigation. Reconnaissance methods, which mainly include remote-sensing and aerial techniques, geological and geomorphological mapping, geophysical and geotechnical techniques, have to be adapted to the characteristics of the landslide. According to Mc Cann and Foster (1990) a geotechnical appraisal of landslide's stability has to consider three following issues: (1) the definition of the 3D geometry of the landslide with particular reference to failure surfaces, (2) the definition of the hydrogeological regime, (3) the detection and characterisation of the movement. Except in very peculiar cases, a landslide generally results in a modification of the morphology and of the internal structure of the affected ground mass, both in terms of hydrogeological and mechanical properties. Mapping the surface area affected by the landslide is usually done by observation of aerial photographs or remote-sensing images (Van Westen, 2004) which indicate the topographical expression of the landslide. However, if the landslide is ancient or little active, its morphologic features and boundaries may have been degraded by erosion and surface observations and measurements have to be supported by reconnaissance at depth (Dikau et al., 1996). Also, the definition of the 3D shape of the unstable body requires the investigation of the slide mass down to the undisturbed rock or soil. Conventional geotechnical techniques, which mainly include boreholes, penetration tests (when possible) and trenching (Fell et al., 2000), allow a detailed geological description and mechanical characterisation (eventually through laboratory tests) of the material, defining the vertical boundary of the slide and the parameters required for slope stability analysis. These techniques only give punctual information and their use is limited by the difficulty of drilling onto steep and unstable slopes.

Geophysical prospecting was applied on various types of landslides for slope varying from a few degrees (earth slide) to a vertical (rock fall). The penetration depth of the surveys ranges from 3 m to 400 m (Dikau et al., 1996) and the targets of the surveys were mainly two. By far, the major one was the location of the vertical and lateral boundaries of the slip mass or equivalently the failure surface.An additional and implicit target is the mapping of the internal structure of the landslide. All geophysical methods such as seismic, electrical resistivity, electromagenetic, gravity and spontaneous potentials were used with this purpose. Four main different situations can occur. In the first case, geophysical contrasts are due to the lithological changes (layering, tectonic contact or pre-slide weathering) and the failure surface mainly coincides with a geological interface or a layer (Batayneh and al Diabat, 2002;

Glade et al., 2005; Jongmans et al., 2000; Agnesi et al., 2005; Havenith et al., 2000; Wisen et al., 2003).

In the second case, geophysical contrasts are also controlled by lithological variations but the failure surface cuts the structure in a more complex way and may or may not be deduced from the geophysical image (Bichler et al., 2004; Ferrucci et al., 2000; Mauritsch et al., 2000; Demoulin et al., 2003), depending on the landslide velocity, the heterogeneity of the material and the resolution of the technique.

Exceptionally (third situation), the failure surface (or potential failure) is directly detected, mainly by propagation methods (Bichler et al., 2004; Jeannin et al., 2005; Petinelli et al., 1996; Willenberg et al., 2004).The propagation of surface initiates rolling contact fatigue (RCF) cracks, which leads to the mode of contact failure known as pitting, characterised by a loss of material from the load-bearing surface in the form of crater-shaped cavities or pits provided that running conditions are sufficiently good to eliminate premature failureby all other mechanisms. Pitting ultimately limits the life of machine components subjected to concentrated rolling/sliding contacts such as rolling element bearings, gears and cam/follower systems . The process of pitting failure involves the initiation of micro-cracks within the stressed volume via a damage accumulation process, subsequently followed by their growth, which eventually leads to the generation of surface pits and the ultimate failure of the component.

In the fourth case, the landslide develops in a globally homogeneous layer and alters its characteristics. The geophysical contrast then arises between the slide and the unaffected mass (Caris and van Asch, 1991; Méric et al., 2005; Lapenna et al., 2005; Schmutz et al., 2000; Lebourg et al., 2005; Bruno and Marillier,2000), from the cumulative or separate action of the mechanical dislocation, the weathering and an increase of water content. The second target of geophysical prospecting is the detection of water within the slip mass, for which electrical (Lebourg et al., 2005; Bruno and Marillier, 2000; Lapenna et al., 2005) and electromagnetic (Caris and van Asch, 1991; Mauritsch et al., 2000) methods were most applied.

2. Area of the study

The study area is located north of Addis Ababa situated in the Tigray regional state. It is bounded by geographic coordinates WGS 84 Zone 37N projection between. (13000' 00" - 14000' 00" N) and (40000' 00" -41030' 00"E) about 770 km away from Addis Ababa. The study area covers the major city of the regional state of Tigray (Mekelle,Hagere-Selam and Abyadi). It has an average altitude of 2000 meters above the mean sea level. In the area densely populated urban centers are often founded on steep slopes.The city is growing into different directions and has to adjust its planning strategies to accomplish the demands of an abruptly growing population. The spatial effects of the surrounding mountain ridges and enclosing landforms have special importance for reservation of specific areas and facilitate development of the city. At present, a significant amount of engineering structures mainly multi-story buildings, roads, bridges are under construction, especially they are concentrated in the north, northwest, and west directions of the city. There is a need for systematic work of detailed engineering geological and geotechnical mapping for Mekelle town and surrounding area. The northern part of Mekelle is situated at the foot of a steep cliff of the Endayesus escarpment on the east side and steep bedded limestone cliff on the northern and northeastern side. The major part of the study area is a gentle slope or a flat lying land. The altitude varies from 2220m at eastern to 1940m in the northwestern part. The climate of the study areas varies mainly according to elevation. According to this classification of the Ethiopian Mapping Agency (1981) the study area is within “WeinaDega” or subtropical climatic zone with altitude 1500-2300 m and mean annual temperature and evapotranspiration of 15-20°C and 1100-1250 mm respectively. It has an annual average rainfall of 530.375 mm/year.

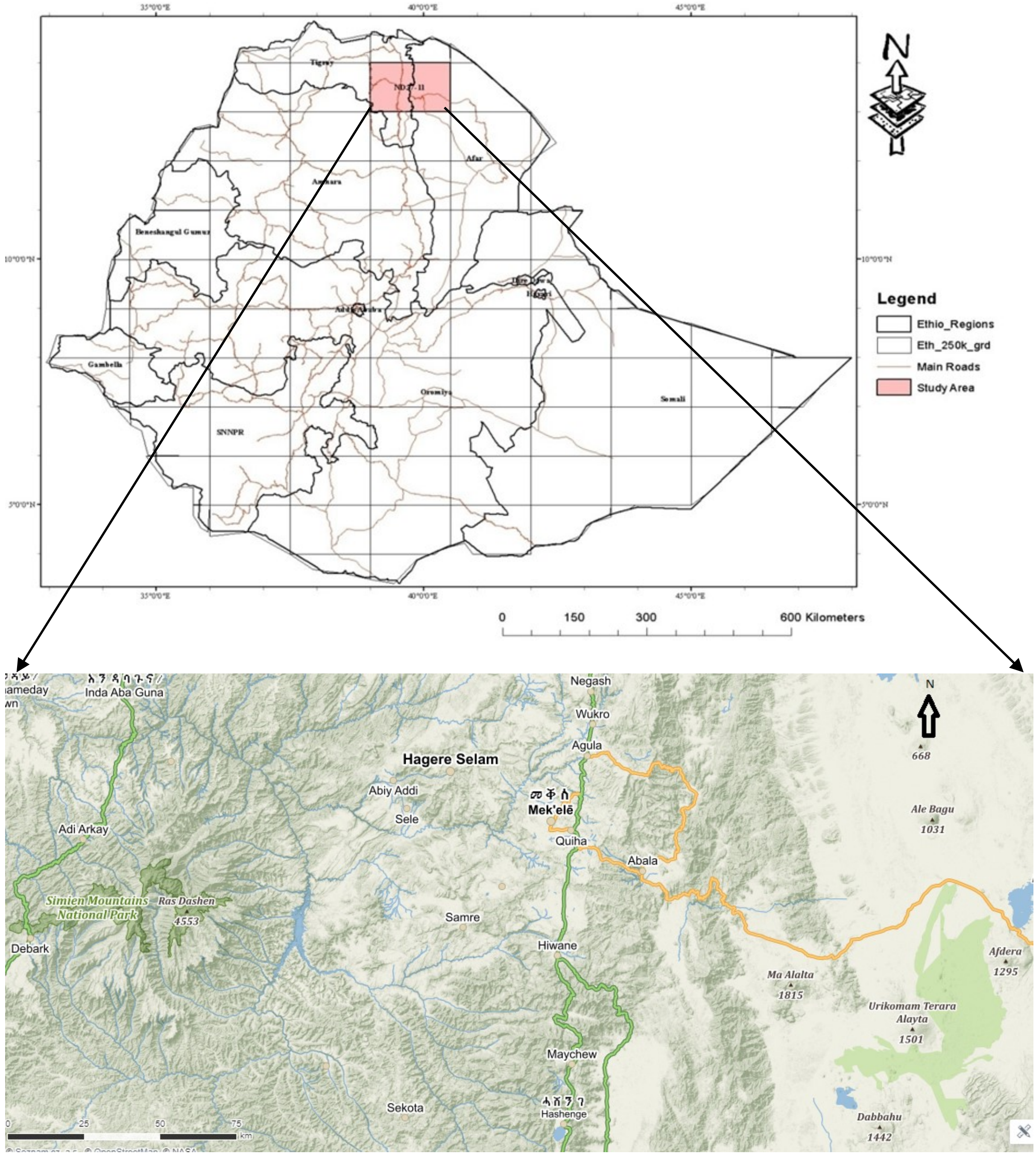


Fig.1 Location map of the study area(detailed map source: Mapy.cz)

3. Geological setting

The East African Orogen is one of the largest orogenic belts on Earth, stretching from Arabia through the whole eastern Africa into Antarctica. Former workers attributed the formation of this orogen to the collision of the already consolidated parts of Eastern Gondwana (Australia, Antarctic, India) and Western Gondwana (Africa, America), leading to the closure of a huge oceanic basin, commonly referred to as the Mozambique Ocean, and a subsequent final orogenic event (i. e. the Pan-African; McWilliams, 1981; Stern, 1994). Recent advances in analytical techniques have led to more precise geochronological data, which point to a prolonged period of metamorphic activity from ca. 650 to ca. 480 Ma, which is much longer than any Phanerozoic orogeny. Therefore, it is still a matter of debate, whether the East African Orogen has to be seen as an accretionary orogen with a continued series of metamorphic events resulting from accretion of microcontinental blocks in the timeframe of 650 to 480 Ma, or if there are just two discrete metamorphic events, at 650–600 Ma and at 550–520 Ma, respectively (e. g., Meert et al., 1995; Meert, 2003; John et al., 2004a,b).

The geology of northern Ethiopia is further complicated by the abundance of Neoproterozoic to Neotectonic structures such as folds, faults and shear zones, and lineaments. According to the general geology of Ethiopia taken from Merla et al. (1973) the survey area lies at the northern tip of the continental part of the East African Rift System. Rocks of precambrian age underlie large parts of western and northern Ethiopia and smaller areas in the south and east of the country. Voluminous piles of mainly Cenozoic volcanic rocks occur in large parts of central and western Ethiopia. Paleozoic, Mesozoic, and Cenozoic sediments occupy the eastern, central, and northern part of the country. The rift valley is covered with relatively young lacustrine sediments and volcanics.

The old crystalline basement of Ethiopia is usually divided into three metamorphic complexes (Merla et al., 1973, Kazmin et al. 1978) namely the Lower, the Middle, and the Upper Complex. The Lower Complex, composed of high grade gneisses, represents older cratonic basement and is exposed in southern Ethiopia. The Middle Complex identified in the southern, eastern, and possibly in the western parts of Ethiopia, is composed of clastic sediments and presumably is a Lower to Middle Proterozoic platform cover. The Upper Complex is the youngest metamorphic assemblage in Ethiopia consisting of low grade rock successions of ophiolitic rocks, andesitic metavolcanics, and associated metasediments, clastic and to lesser extent carbonate sediments (Kazmin, 1978). In terms of the regional context, the low-grade metamorphic rocks of northern Ethiopia fall into the ArabianNubian Shield category, while the medium to high-grade rocks of the south, west and east Ethiopian metamorphic terrain fall into the Mozambique Belt. Regional geological mapping of parts of northern Ethiopia by Levitte (1970) and Garland (1980), and compilation work by Kazmin (1972), are standard references for the geology of the region. These works describe the occurrence of widespread meta-volcanic and meta-sedimentary rocks and mafic to felsic intrusions in the area, as part of the Upper Complex of Ethiopia (Kazmin, 1972). Within the Upper Complex, there are two major litho-stratigraphic groups, namely the Tsaliet and Tamben Groups (Levitte, 1970; Garland, 1980). Other formations are only of local importance. Northern Ethiopia is characterized by highly diversified and laterally extensive coverage of sedimentary rocks of varying genesis. The oldest and sparsely distributed Paleozoic sedimentary rocks known as Enticho Sandstone and Edaga Arbi Tillites are exposed in several places in the region. Edaga Arbi Tillite is the younger of the two and is well exposed in the Edaga Arbi village between Abi Adi and Axum. Typical exposures of the tillit are also found around Abi Adi, Wukro, Abreha-We-Atsbeha, and Hawzen areas. Enticho Sandstone is mainly exposed in Enticho between Adigrat and Axum, but also around Adigrat, Senkata, and Atsbi. The other parts are covered by Mesozoic sedimentary rocks. In northern Ethiopia the Mesozoic sedimentary succession, unconformably overlying the Precambrian basement, forms a nearly circular 8,000 km2 area around Mekelle (Beyth, 1972b). The outlier is composed of a horizontal Triassic basal clastic unit (Adigrat Sandstone), a Jurassic carbonate-marl-shale succession (Antalo Supersequence), and an early Cretaceous Sandstone (Amba-Aradam Formation). The flood basalt of Tertiary age unconformably overlies the sedimentary rocks, which in places are intruded by a network of dolerite sills and dykes (Bosellini et al., 1997). Taken from (Large-scale geological mapping of the Geba basin, northern Ethiopia. Tigray Livelihood Paper No 9, VLIR – Mekelle University IUC Program, 46 pp. ISBN 978-90-8826-134-3).Generally the area is potential of landslides activity due to steep topography, weak geology(unconsolidated materials of sandstone, limestone and marl) and human activitys such as road cutings and farming are the main causes for landslides in the region.

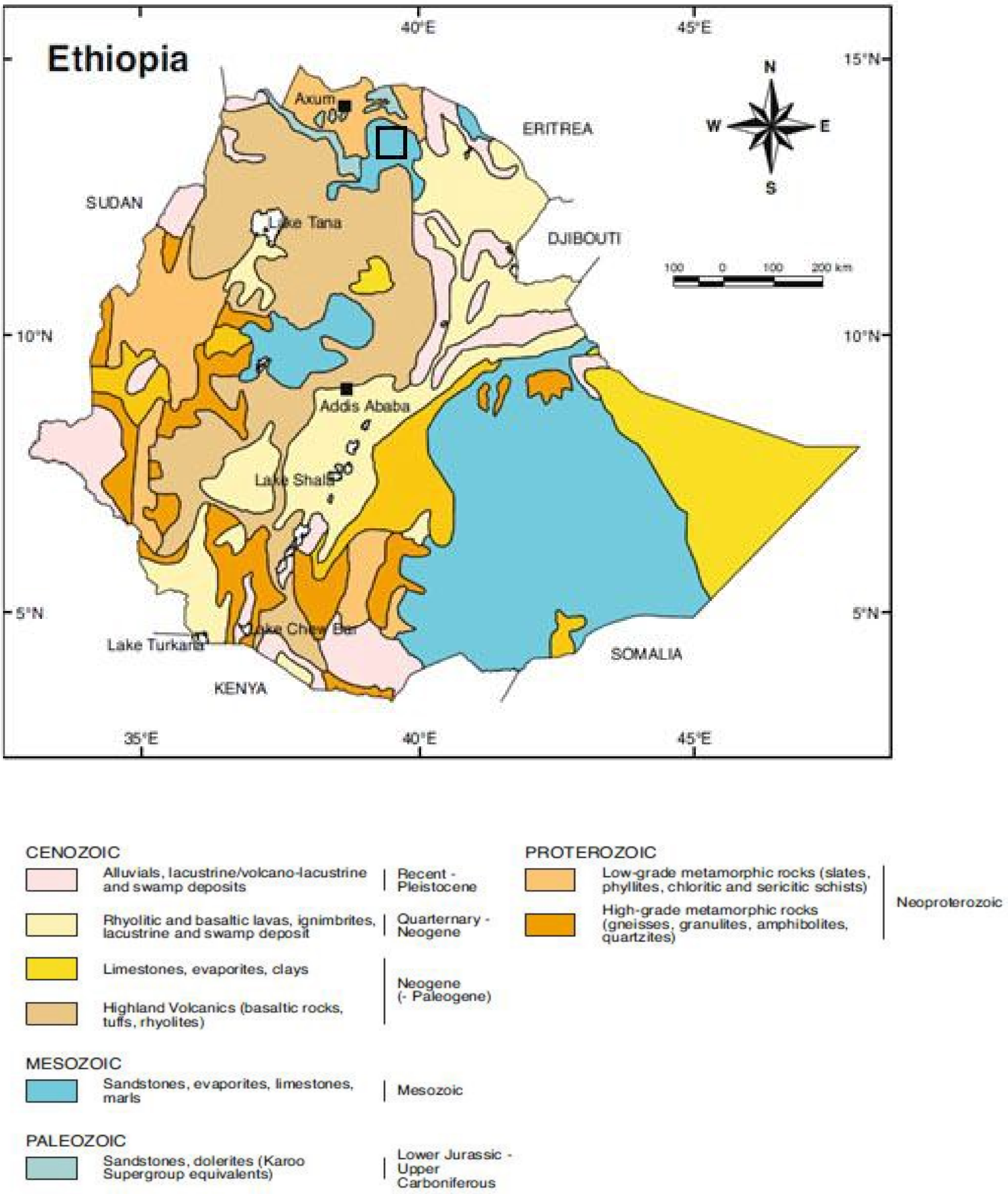


Fig.2 Simplified geological map of Ethiopia (after Merla et al., 1973).

4. Landslides Hazard

The term landslide defined as the movement of a mass of rock, debris or earth down a slope(Cruden et al.,1991). The primary cause of a landslide is the influence of gravity acting on weakened materials that make up a sloping area of land. While some landslides occur slowly over time (e.g., land movement on the order of a few meters per month), the most destructive ones happen suddenly after a triggering event such as heavy rainfall. A landslide is a physical system that develops in time through several stages (e.g., Terzaghi, 1950; Leroueil et al., 1996). As reviewed by Skempton and Hutchinson (1969), the history of a mass movement comprises pre-failure deformations, failure itself and post-failure displacements. Many landslides exhibit a number of movement episodes, separated by long or short periods of relative quiescence. The following definition of the term “failure,” is proposed by Leroueil et al. (1996): Failure is the single most significant movement episode in the known or anticipated history of a landslide, which usually involves the first formation of a fully developed rupture surface as a displacement or strain discontinuity (discrete or distributed in a zone of finite thickness, (Morgenstern and Tschalenko, 1967). The degree of strength loss during failure determines the post-failure velocity of the landslide. The failure stage may involve a kinematic change from sliding to flow or fall, which is also relevant to post-failure behavior and destructiveness of the landslide. Some of the earliest landslide classification systems originated in the Alpine countries. Baltzer (1875) in Switzerland seems to have been the first to distinguish between the various basic modes of motion: fall, slide, and flow. This division persists to the present time, supplemented by toppling and spreading. Several authors, including Heim (1932) and Zaruba and Mencl (1969) focused on landslide types that are characteristic of given material facies described in geological terms.Debris flows represent a particularly important hazard in mountainous terrain and have attracted special attention from early days.

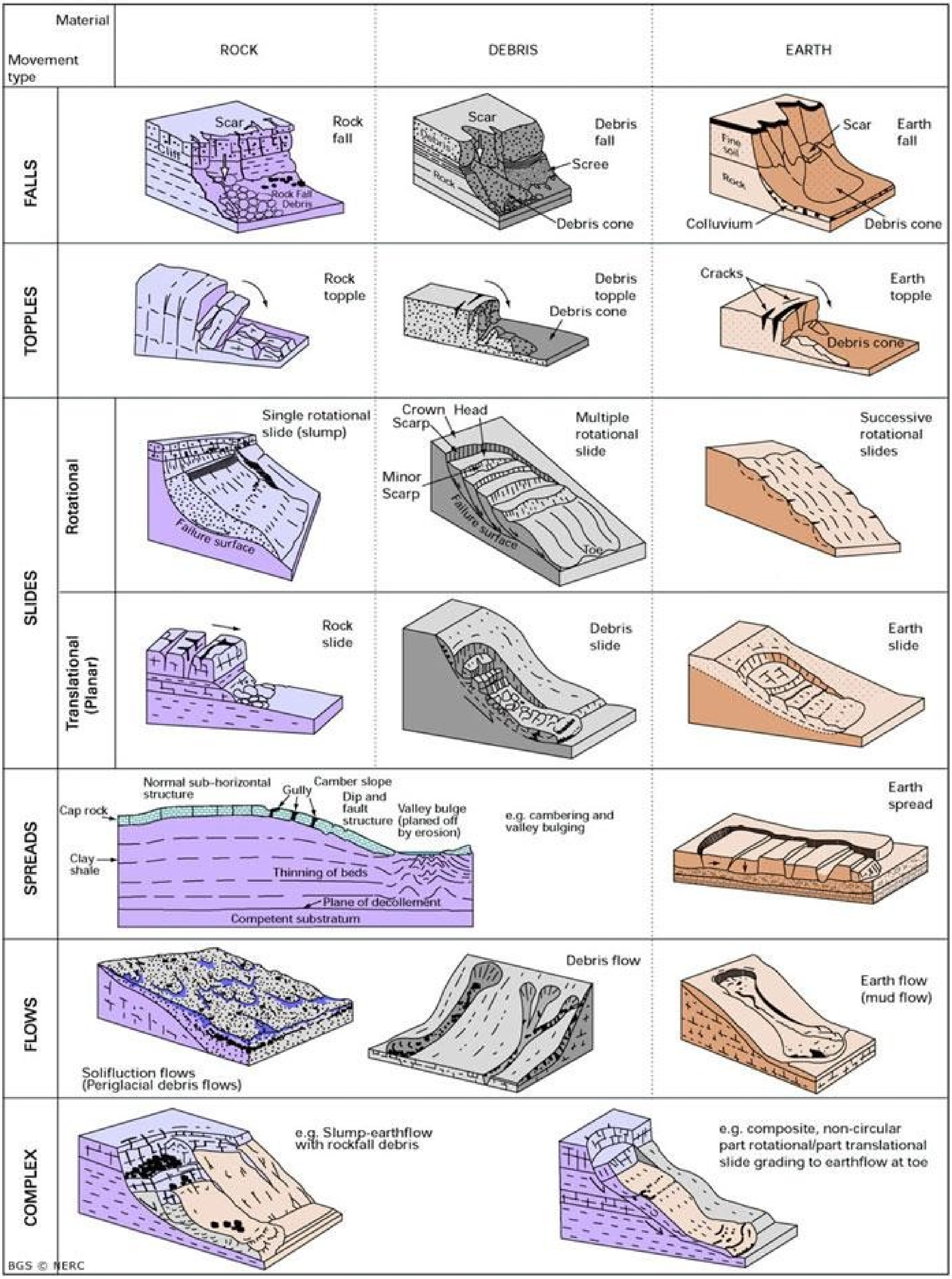
The classic Austrian monograph “Die Muren” by Stini (1910) brings attention to the variety of debris movements in mountain channels, ranging from floods and debris-charged floods (“Muren”) to boulder-fronted, surging debris flows. Similar phenomena have been described in the arid regions of the southwestern USA as “mud flows” by Bull (1964) and others. Debris-charged “hyperconcentrated” floods have been studied extensively on the volcanoes of the US North-West (e.g., Pierson 2005; Vallance 2005).

In the USA, Sharpe (1938) introduced a tri-dimensional classification system recognizing type of movement, material and movement velocity. He also coined (presumably) the important terms debris flow (channeled), debris avalanche (open-slope), and earth flow.

The term “earth flow” was reinforced and thoroughly described in the work of Keefer and Johnson (1983) and is used in North America as a synonym for the British “mudslide” (Hutchinson 1988). The latter word is frequently misused in media reports. Therefore, “earth flow” is preferable.

Sharpe’s framework was expanded by Varnes (1954, 1978) in his influential articles prepared for the Transportation Research Board of the National Research Council in Washington he proposed 29 landslides type based on the type of movement and the type of material. This was modified in 1996 by Cruden and Varnes, to concentrate on the type and rate of movement. The 1978 version of the “Varnes Classification System” was widely accepted by workers in many countries, albeit usually with modifications (e.g., Highland and Bobrowsky 2008; Dikau et al. 1996).

Figure 3: Landslide classification after Cruden and Varnes (1996)



Source: British Geological Survey, 2019

The study site is located in the Northern Ethiopia Tigray Regional States and, as mentioned previously, these areas are formed by the steep slope topography and its common events in the area. The landslide investigations takes place in three different sites which are Adimesno , Hala and Hagereselam localities described hereafter in detail.

4.1. Adimesno Landslide

The land slide is located in the small village called Adimesno, along the main road Addis Ababa to Mekelle.

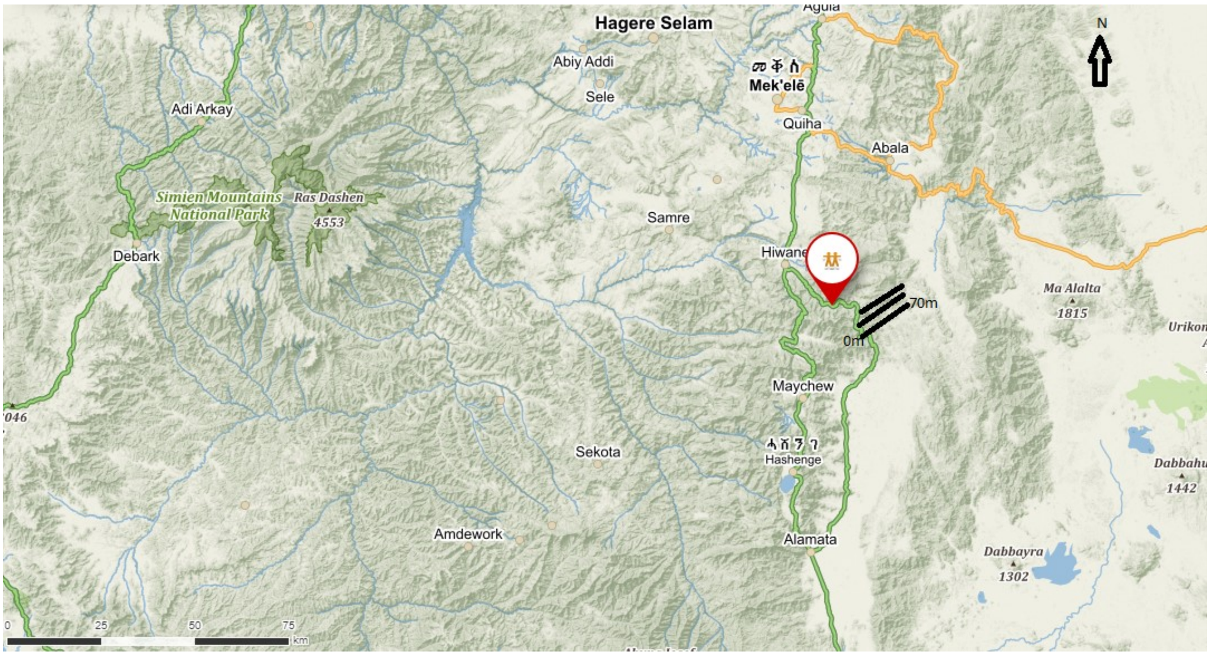


Fig.4: Adi Mesnu landslides (detailed map source: Mapy.cz)

The road here is built on a side of a steep river valley of the NW-SE direction. It is rotational type of landslide. The total length from the top of the land slide to the crown is 50 meters and the width is approximately 100 meters. The average inclination of the cliff is 50°. The bottom of the cliff is formed a limestone unit and the toe part is formed of unconsolidated materials. The road in the locality is impacted by the land slide, which occured most frequently as deep seated land slide failures in the road cuttings, causes temporary partial block the traffic flow and require to be repaired every season. Two longitudinal cracks (l=40m, w=6cm and d=40cm) and two taransverse cracks (l=2.5m, w=2cm and d=10cm) are visible on the body of the landslide repaired by conceret and the bottom part of the landslide is constructed by retaining wall to prevent the movemet but the landslide is still active and unstable especially during the raininy season. The road is on the crown of the landslides and exposed for mass load from vichels triggered by gravity effect to slide easily.

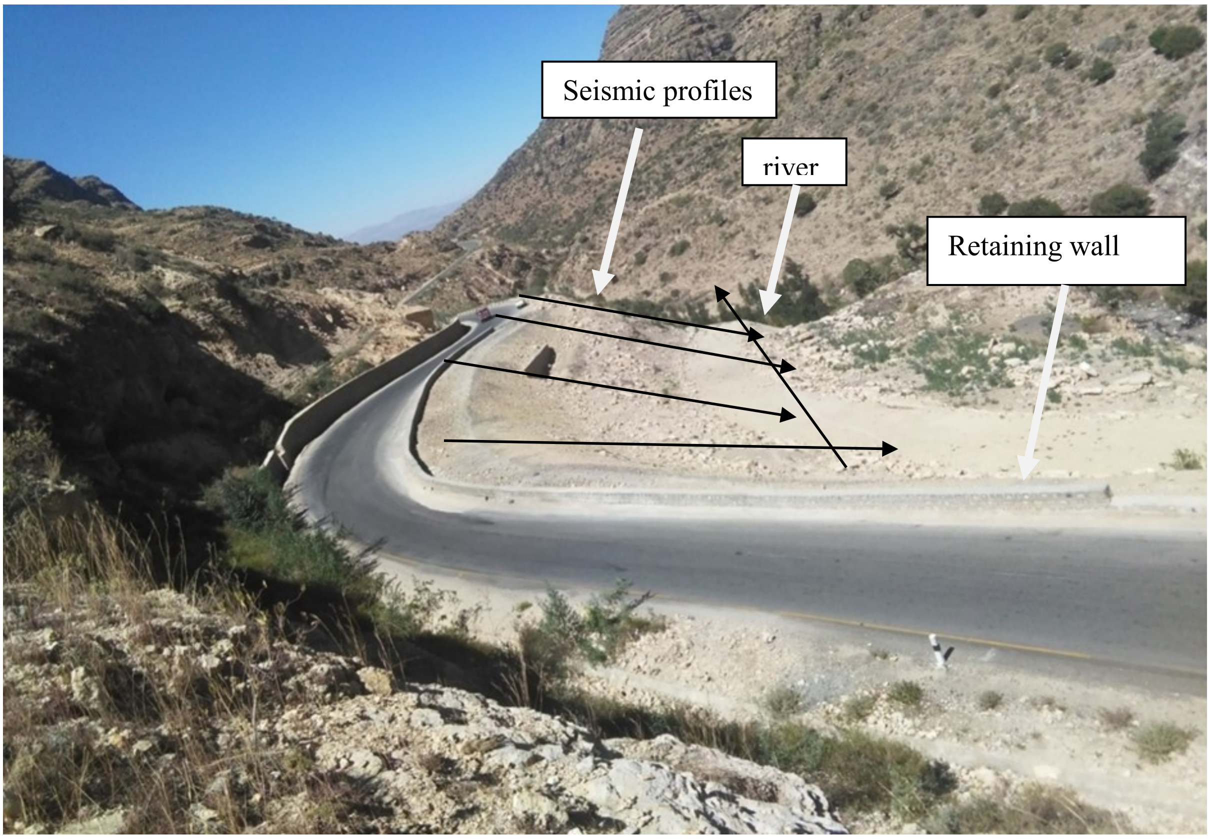


Fig.5. Seismic profiles in Adi Mesnu Landslides

4.2. Hala Landslide

The landslide is a rotational type of landslides distracting the main road between Mekelle-Hager-Selam cities and slightly affects a farm land at the bottom of landslide.The upper part of the landslide is formed of layered, coarse to medium grained sandstone overlaining marl units. The marls in this position (saturated by the rainfall water running through the porous sandstones) are, naturally, susceptible to sliding. The road is therefore often blocked due to the landslides because like Adi Mesnu Landslides the road is on the crown of the landslides and exposed for mass load from Vehicles triggered by gravity effect to slide easily. The total length from the top of the land slide to the crown is about 55 meters and the width of a rupture surface is 13 meters. The main body of the landslide is a mixture of collected materials during constructions of the main road which includes loose, massive, dry, medium to coarse grained, low plasticity, gapgraded, boulder (3cm) and sandy silt soil. An average slope inclination of affected area of the landslide is about 20° and dipping to SE.

Fig.6: Hala landslide(detailed map source: Mapy.cz)

Fig.7: Seismic profiles in Hala landslides

4.3. Hagereselam landslide

This land slide is located near the Hagereselam town characterized by new developing landslide in the center of an old landslide. It is seriously damagging for the road and farming land of the area.The length of the landslide is nearly 30 m and the width is 40 m. It is an active rotational type of a landslide. The main materials of the area is an accumulation of a colluvial material from the top part (a basalt quarry site) overalied with a shale material. The height of the main scarp is 7m with an inclination of 70 degree heading to the northeast. It is dominated by black, firm, massive, dry, fine and grained soil. The landslide material is composed of silty-clay matrix with highly weathered shale overlain by the basalt.

Fig.8: Hagere Selam landslide(detailed map source: Mapy.cz)

The effects are visible on crop land, road and settlements. On the top part of the landslide trap volcanic (Cenozoic age) are thickly stratified. Colluviums material is the most unstable material underlain weak material at bottom. Far from this land slide (at the toe part), there are also sparsely distributed villages and springs nearby the landslide. Newly propagating tensional cracks are common across developing slides and down dropped old road. Within this location developing gully erosion on the across loss material increases affected geometry of slops average inclination estimated 70 degrees on the unaffected original slop.

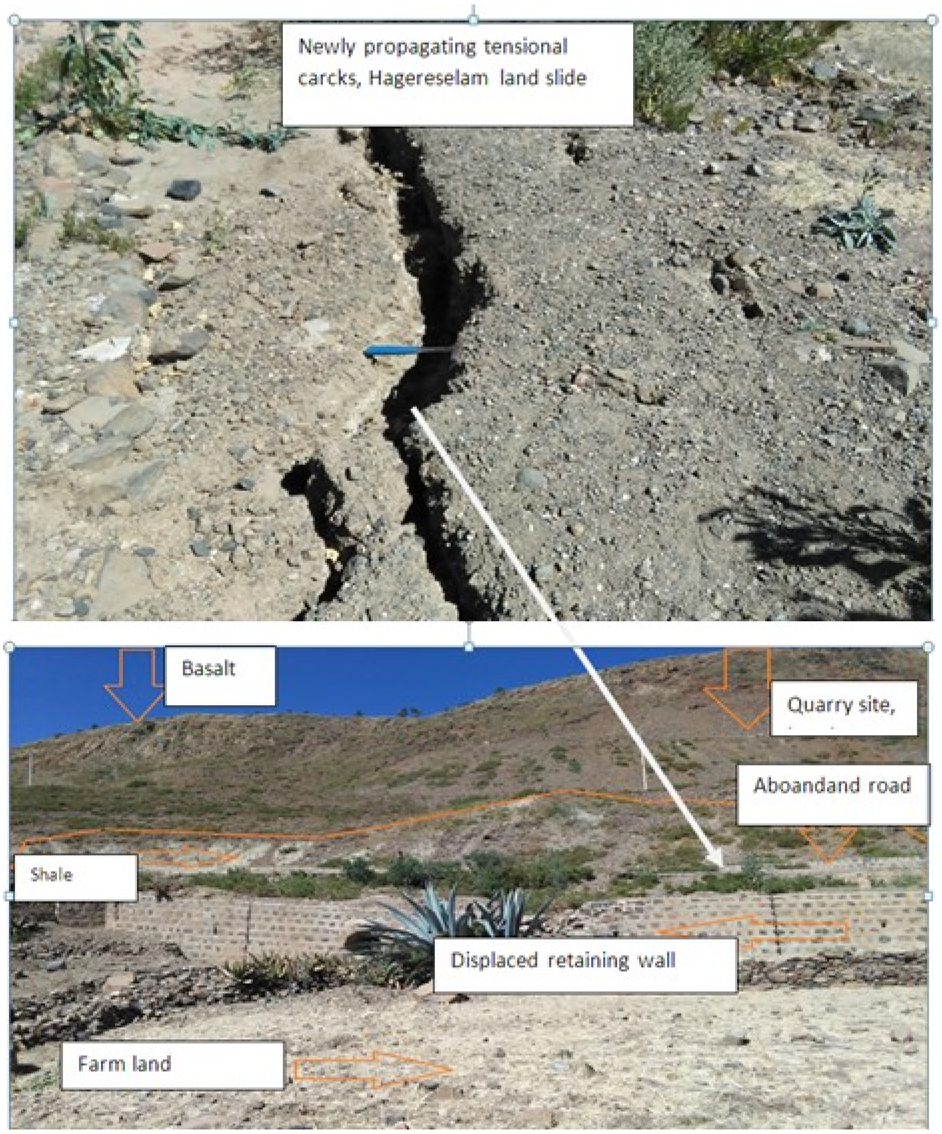


Fig.9: Hagere Selam landslide counter measure works and young cracks

5.GEOPHYSICAL METHODS: AN OVERVIEW

Geophysics is based on the acquisition of physical measurements from which physical parameters can be deduced. A review of the geophysical methods applied at the reconnaissance stage in a landslide investigation was made by Mc Cann and Forster (1990), who illustrated with several case studies from different geological settings. Recently, Hack (2000) presented in a general way and discussed various geophysical techniques for slope stability analyses, quickly examining their merits and illustrating them.The main characteristics of geophysical methods are summarized here. On the one hand, advantages of geophysical techniques are that (1) they are flexible, relatively quick and deployable on slopes, (2) they are non-invasive and give information on the internal structure of the soil or rock mass, and (3) they allow a large volume to be investigated. On the other hand, their main drawbacks are: (1) the decreasing resolution with depth, (2) the non-uniqueness of the solution for a set of data and the resulting need for calibration and (3) the indirect information they yield (physical parameters instead of geological or geotechnical properties). It is worth noting that almost all the advantages of geophysical methods correspond to disadvantages of the geotechnical techniques and vice-versa, outlining the complementarities between the two investigation techniques. A reconnaissance campaign implying geophysical techniques has to be properly designed. The method to apply depends on its adequacy to the problem to solve and on four controlling factors, which have to be thoroughly considered before any field experiment(Mc Cann and Foster, 1990). The first and obvious one is the existence of a geophysical contrast. The presence of a geological, hydrological or mechanical boundary (e.g., the limit of the sliding mass) does not necessarily imply a variation in terms of geophysical properties.The second issue is the characteristics of the geophysical method itself, namely the penetration depth and the resolution (ability of the method to detect a body of a given size).As mentioned above, there is usually a trade-off between resolution and penetration: the deeper-the penetration, the poorer-the resolution. These limits have to be accounted for during the design of a geophysical survey. Due to the indirect information they provide, geophysical techniques have always to be calibrated by geological or geotechnical data to obtain a reliable interpretation. Finally, the performance of geophysical techniques is strongly dependent on the signal-to-noise ratio. Landslide material can be highly disturbed and consequently lead to electrical current injection difficulties or strong seismic wave attenuation. Preliminary tests are always required before designing a survey.After processing, geophysical methods provide the variation of a physical parameter with one, two or three spatial coordinates, corresponding to 1D, 2D and 3D information, respectively. 1D information corresponds to a profile (horizontal or vertical) while 2D and 3D information are geophysical images usually obtained through an inversion process (Sharma, 1997). Geophysical imaging (tomography) has dramatically developed during the last twenty years and has the major advantage to give continuous information of the studied body.Geophysical inversion is a complex and nonlinear problem (Zhadov, 2002) and image interpretation has to be done with a critical mind, considering the already mentioned drawbacks of geophysical techniques and additional limits linked to the inversion process. The obvious and necessary condition an image (model) has to fulfil is that it explains the data, i.e. the forward modelling of the derived image give results close enough to the data. This is usually assessed by a misfit error (RMS) which has to be systematically provided with the image. Even if the RMS value is low (a limit of 5% is usually considered), due to the limited measurement coverage and to errors on the data, the obtained image may only be one of the solutions explaining the data. Depending on the inversion technique, different strategies exist to address this problem of non-uniqueness: tests of inversions considering different starting models, introduction of a priori information in the inversion to constrain the solution, joint inversion of several geophysical data sets. The second issue is the image smoothness caused by most of the inversion techniques used in geophysical tomography, resulting in an inability to determine sharp layer interfaces (Wisen et al., 2003). Also, new techniques for solving this problem are emerging, using a priori information (Wisen et al., 2005), regularization for favouring sharp boundaries in the inversion process (Zhadov, 2002) or image processing tools such as crest lines extraction process in gradient images (Nguyen et al., 2005). Finally, most of the existing images are 2D, while a landslide is a 3D phenomenon. 2D images of 3D structures may be affected by strong artefacts which are very hard to detect (Wisen, 2005). A judicious strategy to tackle this problem is to perform 2D and 3D forward modelling to evaluate the robustness and reliability of the obtained image. In any case, the geological or geotechnical interpretation of geophysical images has to be done by considering all the data available on the site, after a discussion between geologists, geophysicists and geotechnical engineers, and has to be clearly argued and shown (Jongmans, D., & Garambois, S. (2007).

6. Geophysical Methods and Data Acquisition

6.1. Seismic refraction

This method is based on the interpretation of the first arrivals in the seismic signals and assumes that the velocity in general increases with depth (Kearey et al., 2002). It is widely used in engineering geology for determining the subsurface strata and the bedrock depth. For landslide investigation, the method has proved to be applicable, as both shear and compressional wave velocities are generally lower in the landslide body than in the unaffected ground. Mc Cann and Forster(1990) documented several case histories showing the use of seismic refraction for locating the undisturbed bedrock below landslides. In recent studies, the travel time data have been interpreted using the delay-time methods (Kearey et al., 2002) like the plus-minus technique (Hagedoorn, 1959) or the Generalized Reciprocal Method (Palmer, 1981), which allow the mapping of an undulating refractor. The method of seismic refraction is based on the traveltime measurements of the first arrivals, including direct, refracted and diffracted wave phases. The velocity contrast is one of the main parameters controlling the resolution of the method. Since the seismic velocity of a material is a function of its mechanical properties, this may produce useful results in landslide studies for delineating failure surface and determining physical properties of the landslide material (e.g. Bogoslovsky and Ogilvy, 1977; Bichler et al., 2004; Otto and Sass, 2006).

Another possibility of seismic imaging is the seismic tomography (e.g Nolet, 2008). The seismic tomography from surface (all sources and receivers are located on the surface) is a technique which could be use to image lateral and vertical changes in seismic wave velocities and can even resolve the velocity inversion. The only necessary condition is that the seismic velocity in general increases with a depth, usually a model with a velocity gradient is produced by this technique, however a layered model or a combination of both is possible. Several tomographic techniques have been applied to seismic first arrival travel time data (Pullammanappallil and Louie, 1994; Ammon and Vidale, 1993; Simmons and Backus, 1992; Vasudevan et al., 1991; Olsen, 1989). Tomographic methods develop best-fit velocity models by iteratively comparing different velocity structures with observed data to a degree of resolution. However, greater resolution, does not imply improved accuracy (Pullammanappallil and Louie, 1994). The method uses only first arrival time data and profile geometry as input. No initial assumptions of velocity structure or layering are required. Although the initial model close to the supposed structure (fits the data reasonably well) is, naturally, a beneficial since it is not probable that the inversion process ends in a local minima and that the best-fit-model will be closed to the “true” structure. As such, the method is easily applied and is well suited for investigation of areas dominated by complex shallow structure, significant velocity gradients and variable topography. Another advantage of tomography is the minimum curve raypath in the inversion defines a maximum depth of investigation. In cases where insufficient data exist, any tomographic inversion may generate inaccurate models. Therefore, as with the generalized reciprocal method (GRM), multiple shotpoints along a survey profile provides greater data coverage for analysis and helps in generating a more accurate model. The seismic refraction surveys were performed along the three landslide areas in perpendicular and parallel direction of the mass movement. The survey was carried out using high-frequency (20 Hz) vertical geophones and a sledgehammer as a seismic source. The seismic data sets were processed by the tomographic inversion techniques. The field data were processed by picking the first arrival time and producing travel-time curves which could be inverted to form velocity models. The effectiveness of refraction data interpretation depends on reliability of the picking-process. Generally, first-break quality is related to the near-surface structure, source type, signal frequency and signal-to-noise ratio (S/N) conditions. Therefore, the automated picking of first breaks can be a very difficult task if data are acquired in complex near-surface scenarios or if the S/N is low (Yilmaz, 2001). Traditionally, the determination of the first break times is carried out by a visual inspection of the amplitudes, operator's eye estimation capacity and experience, scaling, quality of data imaging and waveform changes (Gokturkler et al., 2008).

6.2. Data acquisition and recording:

6.2.1. Field Surveying

During the, majority of surveys, the P wave data are usually analysed, however the S wave data are also occasionally recorded. The advantage of measuring the S-wave velocities is their direct connection with geotechnical parameters (Lamè parameters). Moreover, the sensitivity for a mechanical disintegration (fractures, joints, weathering) is higher for S-waves as well. Unfortunately, the processing of S-waves is more difficult then of P-waves. The S-waves are slower then the P-waves and thus can never be simply and easily identified as first breaks and, moreover, the special S-wave sources do inject less energy to the ground then the simple P-wave sources implying lower depth reach and lower S/N ratio of S-wave prospection. Therefore, despite the advantages of S-wave measurements, the P-waves are usually the choice number one for the prospection.

Typically, the spreads of 24 geophones are laid out to record a shot along a cable, with takeouts to which the geophones can be connected. Geophones and cable comprise a spread. Often between 5 to 7 shot points with 5m geophone spacing take place at each spread of the profile. A common source of a seismic energy is a sledge hammer struck against a metal plate. The low energy of the sledge hammer struck (compared to explosives) is compensated by the stacking – several hammer blows are summed together to amplify the coherent signal (the seismic energy from the hammer) and reduce the incoherent noise and as a reesult increasing the signal-to-noise ratio parameter.

6.2.2. Instrumentation

For this survey the OYO McSeis-SX24 seismograph was used. A seismograph generally consists of sensors (geophones), a low-pass anti-aliasing filter, analog to digital (A/D) converter, and a recorder. Modern digital seismographs are complicated by the extensive electronic circuitry involved. The McSEIS-SX seismograph used is portable instrument with 24 channels for 24 geophones. It can be used for a refraction exploration, downhole P-S velocity logging and a cross-hole seismic for engineering and construction. The system is compact, light in weight to transport and does the job with a small 12VDC battery. It is based on the Windows XP SP2 professional with XGA/TFT colour display, hard disk drive, USB ports and reliable field performance. For positioning the profiles and measure their coordinates we used the Garmin GPS receiver.

6.3. Data processing and Interpretation for seismic refraction

Refraction survey is used to calculate depths of the sliding surfaces and the lateral extent of landslides (Cummings and Clark, 1988; Palmer and Weisgarber, 1988; Bogoslovsky, 1977; Brooke, 1972; Carroll et al., 1972; Trantina, 1963). The basis of the interpretations is the difference in the physical properties such as seismic impedance and porosity of the sliding materials and the subsurface undisturbed sediments and bedrock that result in different seismic velocities (Abramson et al., 2002). In addition to delineating the extent of a slide mass, refraction surveys can also provide data relevant to construction, rippability and earthwork factor (Stephens, 1978). The main advantages of refraction surveys in landslide investigations over other methods are that the environment is not disturbed, the equipment is portable, and the technique is relatively inexpensive (McGuffy et al., 1996). Intercept-time and reciprocal methods of interpreting refraction data can be used to model velocity structures of the landslides. These methods are most applicable to in the area where subsurface layers dip less than approximately 20° (Palmer, 1981) and have nearly homogeneous velocities, for these methods assume a layered model and continuity of refractor surfaces across a profile. However, the velocity pattern of landslides can be complex, making them difficult to accurately model using intercept-time and reciprocal methods. Lateral and vertical changes in velocity, steeply dipping and discontinuous refractors, and diffractions from blocks within the landslide mass are features commonly observed in refraction surveys of landslides. One limitation of seismic refraction is the inability to recognize the existence of certain layers, referred to as hidden layers or blind zones, because of insufficient velocity contrast or layer thickness (Redpath, 1973). Another limitation of seismic refraction method using the traditional layer-based techniques is incorrect depth calculations to certain layers where velocity reversals exist, i.e., where layer velocities do not increase with progressive depth (Redpath, 1973). Refraction tomography is another method of analysing seismic refraction data using a gridded, inversion technique to determine the velocity of individual 2-D blocks within a profile as opposed to modeling velocities as layers. As a result, refraction tomography can, in some cases, more accurately model and provide better resolution of complex velocity structures (e.g. the areas with a velocity gradient or the hidden layers). A discussion of the strengths, weaknesses, and cost effectiveness of seismic refraction surveys is presented in Rucker (2000).

In most refraction analysis, we only use the travel times of the first arrival picking on each recorded seismogram. As the seismic velocity increases at an interface, the critical refraction will become the first arrival at a certain source-receiver offset. The onset of the first seismic wave, the first break, on each of the seismograms is identified and its arrival time-picked.

The travel time curve-analysis of seismic refraction data is primarily based on interpretation of the critical refraction travel times. Plots of seismic arrival times vs. source-receiver offset are called the travel time curves. The delay-time methods calculates refractor depths for each geophone location using overlapping refraction arrival times from both forward and reverse shots, warranting multiple shots along a profile. Multiple shotpoints along a survey profile permit interpretations of changing interface depths and layer velocities.

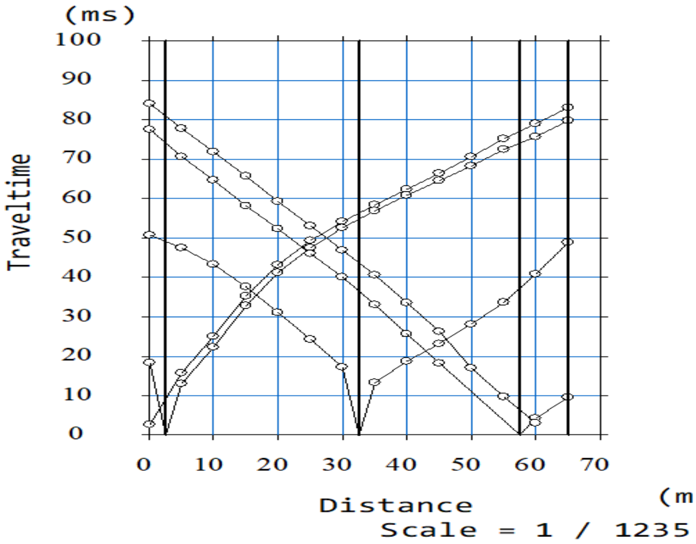


Fig.10: An example of a travel-time curves of the Adi Mesnu profiles

6.3.1. Interpretation of Refraction Travel-time Data

The necessary condition for the refraction method is that the refracted first arrivals from each layer should be detected on a seismogram as first arrivals, and this is possible only when velocities of all underlying layers are successively greater. The usual procedure to interpret the refraction travel times is to fit such a data set with several intersecting straight lines making it a visual technique which may lead to errors of subjective judgment, as the velocity model depends on the selection of various line segments through the data (Steinhert and Meyer, 1961). After the completion of refraction survey first arrival times are picked from seismograms and plotted as traveltime curves. Next, the seismic tomography is used to infer interface depths and layer velocities. The seismic tomography method was used because, as stated before, the layer-based data processing techniques (e.g. the General Reciprocal Method) are effective only when the velocity structure is relatively simple and refractors are gently dipping (<20°). However, the velocity structures of landslides can be complex, making them difficult to model using these methods. In contrast, the refraction tomography, is a method of interpreting seismic refraction data, is well suited for investigation of areas dominated by complex shallow structure, velocity gradients, and variable topography. Regardless of the technique used to interpret the data, multiple shotpoints along the survey profile provide greater data coverage and potentially more accurate models. Where insufficient data coverage exists, the GRM cannot be performed and tomographic analyses may produce unrealistic models. It is prudent to perform both reciprocal methods as well as tomographic analyses, as the different models can compliment one another and when in agreement, increase confidence in the interpretation.

6.3.2. Travel-time inversion of first-arrival data

First-arrival seismic traveltimes can be picked reliably from seismic records and can be inverted to obtain possible distributions of the causative subsurface velocity. Typical tomographic inversion algorithms make use of ray tracing in one or more ways. Bois et al. (1972) developed an algorithm in which curved rays are traced through a velocity medium to solve the forward problem to calculate first-arrival traveltimes. First-arrival ray tracing can be problematic when shadow zones exist or where multiple paths between source and receiver are possible (Vidale 1988). Where multiple paths exist, ray tracing provides no guarantee that a located path corresponds to a first or later arrival (Rawlinson et al. 2007). Due to the non-linear nature of the traveltime tomography problem, new rays must be traced every time the velocity model changes within the inversion algorithm and ray tracing can therefore become computationally impractical when many source–receiver pairs are considered. The inversion scheme requires finding a tomography solution to the following system by an iterative manner.

$$\begin{bmatrix} \sqrt{W_d}J \\ \lambda W_m \end{bmatrix} \Delta m = \begin{bmatrix} \sqrt{W_d}\Delta d \\ 0 \end{bmatrix},$$

where W_d is the data weighting matrix, J is the Jacobian matrix including the partial derivatives of the traveltimes with respect to the model parameters (i.e., slownesses), λ is the trade-off parameter or damping parameter between data misfit and model smoothness, Wm is the weighting matrix of the model parameters (the regularization matrix), Δm is the parameter correction vector and Δd is the travel time residual vector. The data weighting matrix W_d is a diagonal matrix consisting of the reciprocal of the standard deviation of the data. For simplicity, it was assumed as an identity matrix in this study implying that the data were uniformly weighted. A Laplacian smoothing was used for the parameter weighting matrix W_m. To stabilize the solution, the amplitude of the elements of the matrix W_m was increased by 10% for each deeper row (Loke and Barker, 1996).

Ray tracing can be avoided in the forward solution by calculating the first-arrival traveltimes with a finite-difference approach on a discretized domain. A thorough review of seismic ray tracing and wave front tracking via finite-difference approaches is provided by Rawlinson et al. (2007). Aldridge & Oldenburg (1993)developed an inversion approach that uses the finite-difference algorithm of Vidale (1988) in place of ray tracing for the forward solution. Rawlinson et al. (2006a,b) also used a finite-difference modelling approach in 3-D teleseismic tomography problems, employing the subspace inversion method of Kennett et al. (1988). The most important part of the inversion scheme is the computation of the Jacobian matrix. Following Ammon and Vidale (1993). The matrix can be constructed by numerical differentiation (i.e. without tracing rays). This approach is based on the perturbation of the slowness of each cell and the calculation of the partial derivatives by the forward-difference formula (Lines and Treitel, 1984). In the present study, each cell was perturbed by +0.6% slowness. Iterative solution of the equation above requires the recalculation of the Jacobian matrix J at each iteration. Construction of this matrix is a computationally expensive and time consuming operation. This difficulty can be overcome if the Jacobian matrix is substituted by a numerically obtained approximation (Broyden, 1965). Thus, after the third explicit calculation of the Jacobian matrix can be obtained by the

Broyden's updating formula.Accurate calculation of the first-arrival traveltimes is very important in traveltime inversion. At the end of each iteration, the traveltime residual was calculated by the following formula.

$$\mathrm{RMS}_j = \sqrt{\frac{1}{M}\sum_{i=1}^{M} \left(t_i^o - t_i^c\right)^2},$$

Where, M is the number of observed traveltimes, t^o and t^c are the observed and calculated traveltimes, respectively. i denotes each observation, and j denotes iteration.

7. Results

The resulting velocity models of the seismic surveys indicate a three-layered velocity distribution along the profile and display an average depth of 10 m. The soft formations in the area and a low energy seismic source are the reasons for shallow depth penetration of all the profiles. The images are obtained with a low reciprocal time error which is below 5% and the end of 6 iterations with a traveltime residual of 1.75 m/s. The velocity model ranges are between 50-1200 m/s which characterizes low velocity of the subsurface. A layer of the low velocities clearly represent the landslide material and they show an increase with depth. Also the failure surface illustrates an increase in its depth indicating an accumulation of the landslide material.

In Adi Mesnu landslide site (fig.11) the seismic survey carried out in the perpendicular and parallel direction of the landslide the values of P-waves velocities are ranging from 100-1100 m/s and 200-850 m/s respectively. The velocity model essentially shows low-velocity slide material (unconsolidated) overlying a compact layer with a higher velocity. The high-velocity material at the base of the profile is interpreted as weathered limestone and dips southeastward toward the river. The velocity distribution supports an arcuate slide mass characteristic for a rotational landslide. The undulating surface of what is interpreted as the refractor may be an indication that fracturing and displacement extends into the depth. Based on the tomogram and field observations, the active slide mass with velocity values between 100-700 m/s is interpreted to be superimposed on a larger slide, with fracturing and displacement extending into the depth.In Hala landslides (fig.12) the velocity ranges from 100 m/s to 900 m/s and interpreted as coarse to medium grained sandstone overlaining marl units.The marls in this position (saturated by the rainfall water running through the porous sandstones) are, naturally, susceptible to sliding. Simirites were noted in all profiles and the landslides are mostly active during the rainy season when the ground water level increases and the shear strength of materials decreases. In Hagere Selam landslide (fig.13) three seismic profiles are conducted along the perperdicular directions. The velocity is low (50-1200 m/s) in the landslide due to accumulated of colluvial material from top part (qurry site of basalt) overalay shale material which is mass sliding down to the slope of steep topography. The increase of the velocity from 50 m/s to 1200 m/s with depth within the landslide material can be explained by the presence of the water-saturated Zone and some accumulated basaltic colluvials.

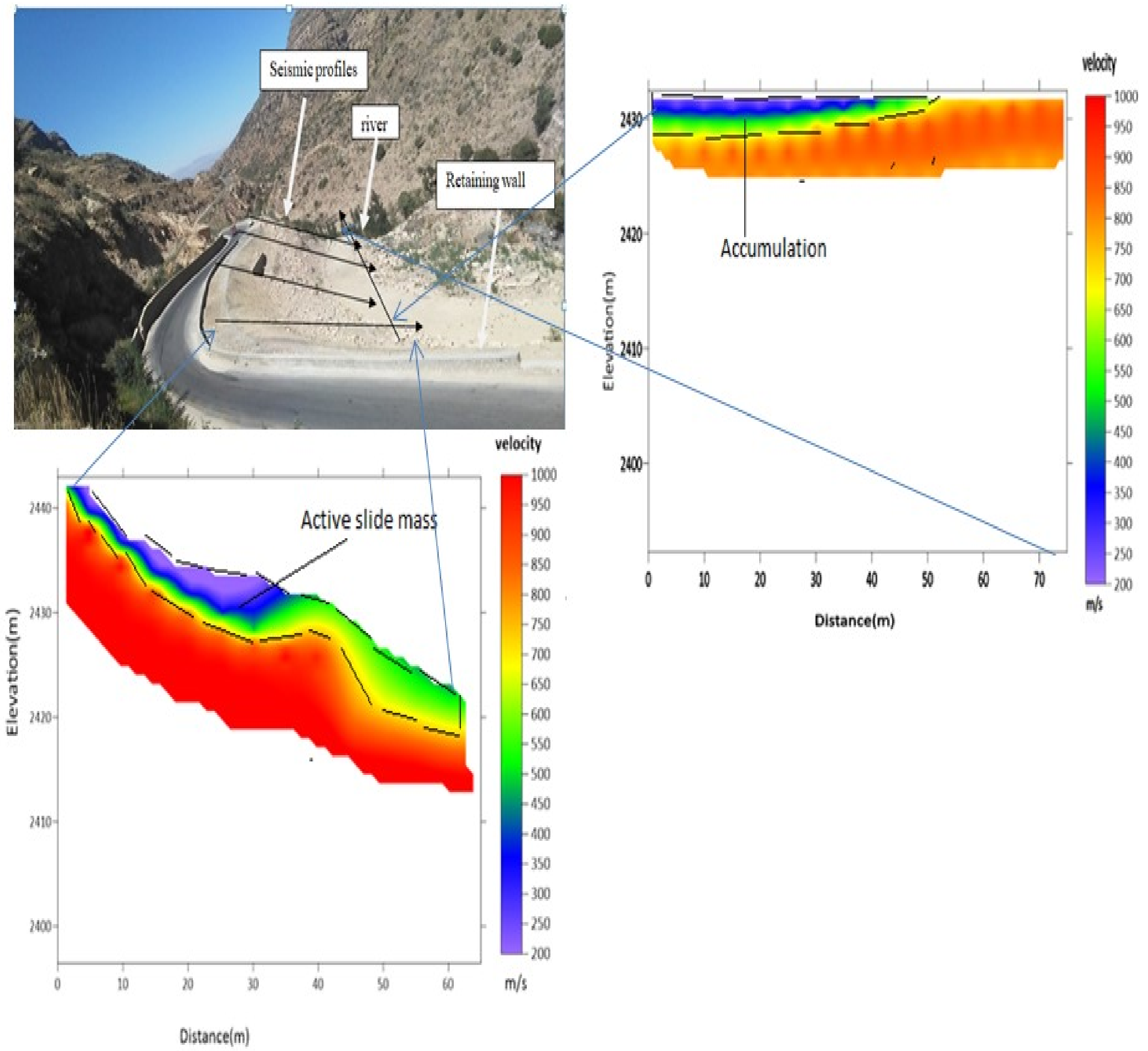


Fig.11: Adi Mesnu landslide seismic profiles

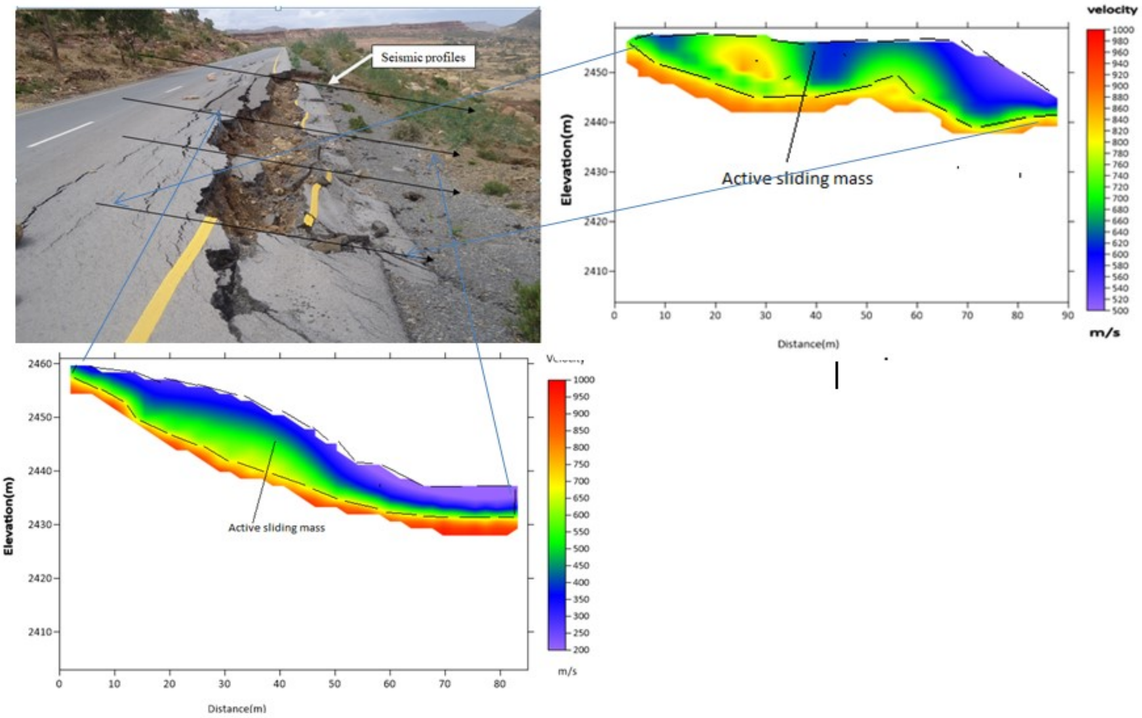


Fig.12: Hala landslid seismic profiles

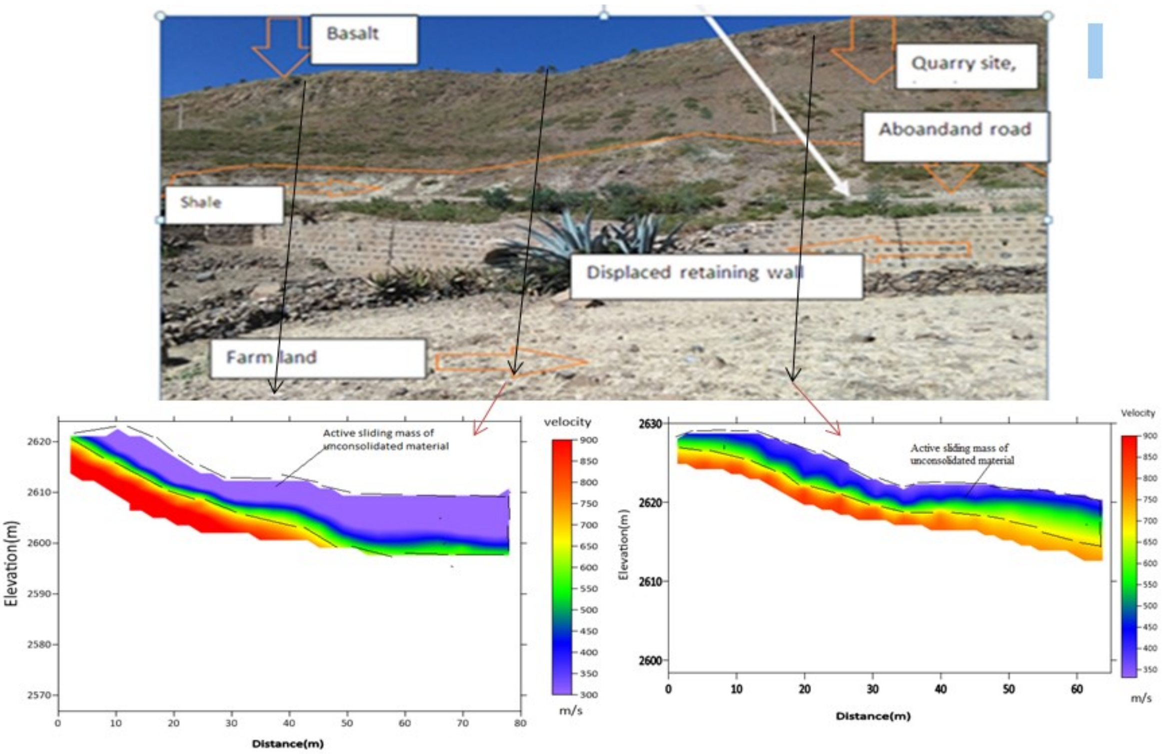


Fig.13:Hagere Selam landslides seismic profiles

8. Discussion

Landslides are complex structures exhibiting a wide variety of geological, geomorphological and hydrogeological properties. Investigation of such heterogeneous structures is one of the most challenging themes for near surface geophysics. The development of 2D and 3D geophysical techniques has aroused a growing interest for assessing the landslide volume, characterising the physical properties of the landslide material and locating the groundwater flows within and around the slide (Jongmans, D., & Garambois, S. (2007). The design of a geophysical survey for landslide recognition is still a much debated question and no unique strategy came out (Denis Jongmans and Stéphane Garambo, 2007). Seismic refraction is a useful geophysical tool for investigating landslides. The velocity structure, depth to the failure surface, and lateral extent of a landslide are variables that can be estimated from analyses of seismic refraction data. The apparent vertical displacements in the bedrock refractor may indicate the landslide is a deep-seated feature incorporating bedrock as well as surficial deposits. The velocity distribution of a landslide along the landslides can be explained by a rotational slide superimposed on a larger landslide with fracturing and displacement extending into the depth.

In the study area surroundings and different parts of the country many seismic refraction surveys have been studied and assessed for existing slope instability by the Geological Survey of Ethiopia. The results of integrated survey are discussed in terms of the main geologic conditions: lithology, tectonics, hydrogeology and engineering geology where each area of investigation is assessed in terms of the prevailing landslide problem.In this section, the independent results of the geophysical survey method, that were brought together to produce the final analysis and interpretation are used to present our findings.

a) Lithologies

According to the geology of the area (fig. 2), the sliding area is underlain by unconsolidated sandstone, limestone and marl intercalated by thin layer of shale in some areas. The rocks are highly weathered and have massive joints irregularly fractured. In some places the limestone aperture in filled by soft material with some conglomerate and its karsted. These conditions favor water percolation and weathering which in turn gives rise to decrease of shear strength and ultimate soil and rock dislocation. The types of lithologies susceptible to the slide flow complex are unconsolidated slope wash deposits or colluvial soil, soft pyroclastics, weathered aand fissured rocks (Abadi et al., 2017).

b) Tectonics

Geologic structures such as faults and folds are the architecture of the earth's crust. Geologic structures influence the shape of the landscape, determine the degree of landslide hazard and bring old rocks to the surface. Structural evolution of the area is linked to faulting and tectonic movements of regionaly widespread rock deformation. The basement rock are tilted N25E in the study area. Two major fault belts are found in the area namely, Mekelle fault (65 km NE) belt and Chelekot fault belt which results in large tilted blocks along the fault line. Moreover, cracking and fracture lines are observed in the present study which may conform this the trend of landslide scarp and faults (Abadi et al., 2017).

c) Hydrogeology

According to the integrated hydro-geophysical results the entire study area lies in a thick saturation zone. Water permeability however, varies in the area depending on the degree of weathering and fracturing of rocks. Very highly decomposed (in to clay) rocks and massive or relatively fresh ones are virtually impervious. Moreover the study area is situated within regions hydro geologically classified as extensive aquifer with fracture permeability characterized by medium productivity. However, heavy winter, high intensity rainfall results in saturation of top soil and increase in ground water level, these conditions affect the weight, volume, internal water pressure and internal cohesion of the materials (Abadi et al., 2017).

d) Engineering Geology

The classification of rock materials based on their strength behavior provides a simpleand fast solution to determine the type and application of support system as well as the method for open-ing underground structures. Intact rock materials are generally classified with regard to the strength, such as uniaxial compressive and point load strength. Rock masses, which are generally classified from poor to excellent, comprise rock material, also called intact rock, and discontinuities. The physical and mechanical properties of rock material are characterized by several parameters, including mineral composition, rock fabric, porosity, strength, hardness, brittleness, and durability (Singh and Goel, 2011). Rock material strength is important to understand the potential behavior of rock mass under dynamic and static loads and must be determined to design constructions in a rock mass environment. The characterization parameters of rock materials are mostly determined in the laboratory as well as in situ studies, and; the design of constructions based on emperical, numerical, or analytical methods is based on the mechanical and physical properties of rock materials and discontinuities. The reliability of any engineering design is highly correlated with the reliability of the input parameters, even if there is a different source of uncertainty (Abadi et al., 2017).

Thes test method (point load tes and scmidt hammer test) were performed in the field.The test is typically used in the field because the testing machine is portable, little or minimal specimen preparation is required, and specimens can be tested within a short time frame of being collected. It help to recognise potential difficulty ground conditions prior to detailed design and construction to identify areas susceptible to failure due to geological hazards to establish design specifications for selection of site for engineering purposes and engineering materials for construction. The most important roles of the engineering geologist is the interpretation of landforms and earth processes to identify potential geologic and related man-made hazards that may impact civil structures and human development. The engineering property of the sliding prone zones in the study area in general lies on low rock mass strength, highly weathered and very closely spaced joint. irregularly fractured. Samples were easily broken with free hand, fine to medium grained and the joint spacing ranges from 1.4m to 2.4m along strike and 2.4 to 1.7m along dip direction. The condition of discontinuity roughness at large scale is straight and rough undulating at small scales. The average rock material strength value calculated from point load test for 3 rock samples ranges from 0.31Mpa to 1.44Mpa. The unconfined compressive strength calculated from point load test result ranges from 7.13Mpa to 33.08Mpa.Furthermore the UCS value obtained from Schmidt hammer is 19.5Mpa to 22.4Mpa.The intact rock strength is 12.5-50Mpa which is lumping broken by light hammer blow. The mean water absorption, porosity and bulk density obtained from representative samples are 6.43%, 14.42% and 2.42gm/cm. Based on the engineering geological investigations heterogeneous rock units were mapped attending to weathering degree, joint intensity and strength, soils in the study area are classified and mapped as alluvial and colluvial soils according to their genesis (Abadi et al., 2017).

In general from the present studies it is assumed that the seismic refraction studies in the landslide area concide with the previous sudy results. The integrated engineering geological and geophysical survey have furnished useful information with regards to lithological, hydrogeological, structural and geotechnical conditions of the subsurface underlying the study areas. The combined interpretations have identified the causes of the landslide, the thickness of landslide mass and depth to the bed rock. The study has also assessed and reported the type and physic-mechanical properties of soils and rocks.

The present investigations have also assessed and appraised the prevailing geodynamics of the area. As a result, slide (active and old) flows were recognized and mapped. The active slides with their accompanying cracking and subsidence were concentrated on northeastern part of Mekelle town. Their type and distribution is mapped and causes and remedies were suggested. The severity of landslide effect is ranging from complete collapse of the main road and farming land of the community. These properties are damaged because they are located on or at the vicinity of the main landslide scrap zone. In the affected area the major sheared zone, which has been affecting the access road to Hagereselam town consists of loose unconsolidated material. This zone is identified as a relatively weak zone due to probably shearing and fracturing of the formations. The velocities in this area vary between 300m/s to 650m/s in the landslide body and slip zone. In addition, tensional soil cracks were observed in the area. The loose nature of the unconsolidated material, surface and groundwater activities are found to be the triggering problems. The geomorphological conditions, the northeast trending fault (Mekelle and Chelekot fault) are responsible for the formation of slopes where the present slope instability processes are taking place.

9. Conclusion

In this study, the seismic refraction tomography techniques were used for the investigation of a landslide site. The technique is very useful for revealing internal structure of the landslide, determining physical properties of the landslide material and delineating failure surface geometry. According to these results, the landslide mass was characterized by the low P-wave velocity. An undulating sliding surface is present along the profiles. The landslide material gets thicker in the middle and the northern parts (the toe area) of the profile. The main causes of these landslides are geological, morphological and human activity. The accumulated material (talus) on the bottom of the limestone cliff is the unconsolidated material. The main road going through the landslide, causes load on the crown of the landslide and easily slides towards the bottom parts especialy during the raininy season.The landslide deposit in the area mainly consist of loose unconsolidated material, i.e, the instability problem is associated with the unconsolidated material. The thickness of these deposits ranges from 4m to 9m. In addition to the geoogical condtion, surface and ground water are also found to be the aggravating factors, which are manifested by the presence of seepage zones at the contact between the overlaying unconsolidated material, and underlying weathered limestone bedrock. In addition, tensional cracks are also common on the sliding mass forming parallel pattern, perpendicular, to the sliding directions. The zones representing the main landslide instability features of the area, slides with their active scrap, cracking and subsidence, coincide with geophysically delimited active slide zones. Zones or horizons with such nature and physical and mechanical properties are characterized by very low velocities below 1000 m/s. To reduce and mititigate these hazared proper counter-measure works are required. The hazard can be reduced by avoiding construction on steep slopes and existing landslides, or by stabilizing the slopes. Stability increases when groundwater is prevented from rising in the landslide mass by (1) covering the landslide with an impermeable membrane, (2) directing surface water away from the landslide and (3) draining ground water away from the landslide. In different parts of the country these counter-measure works are applied and it is effective to mitigate the landslide hazard. Slope stability is also increased when a retaining structure and/ or the weight of a soil/rock berm are placed at the toe of the landslide or when mass is removed from the top of the slope. In all the three areas, seismic refraction surveys and analyses of the data will aid in characterizing the landslides and provided information important in determining appropriate mitigation and maintenance measures.

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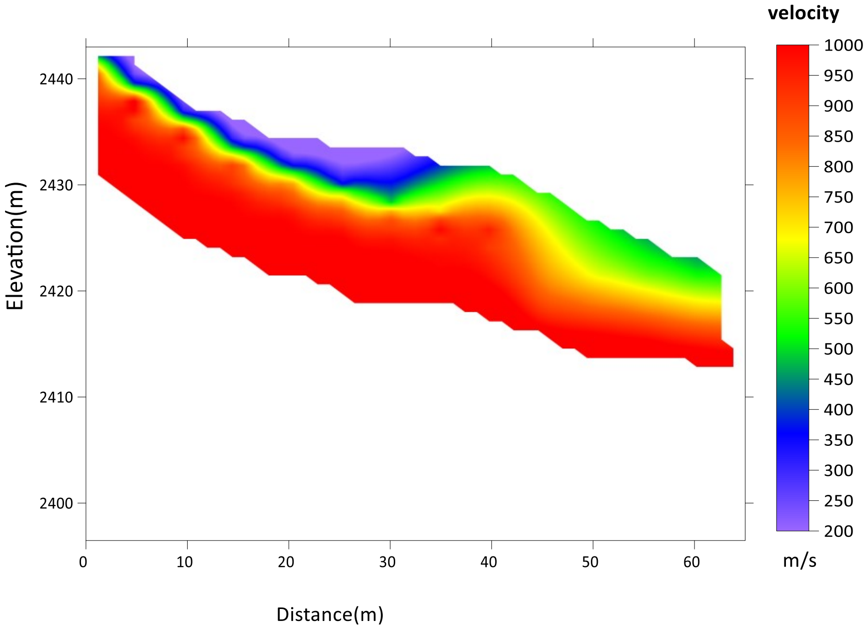
Appendexes

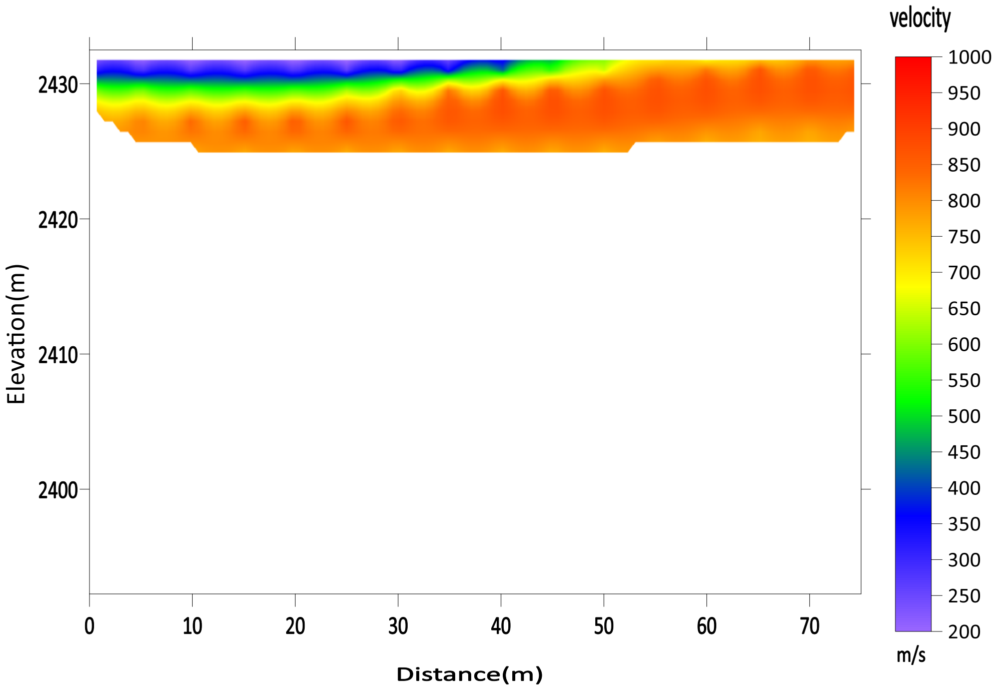


Adi Mesnu Landslide Profile 1

<u>Key for Adi Mesnu landslide profile 1</u>

200-600 m/s - unconsolidated material

650-1000m/s -weathered limestone

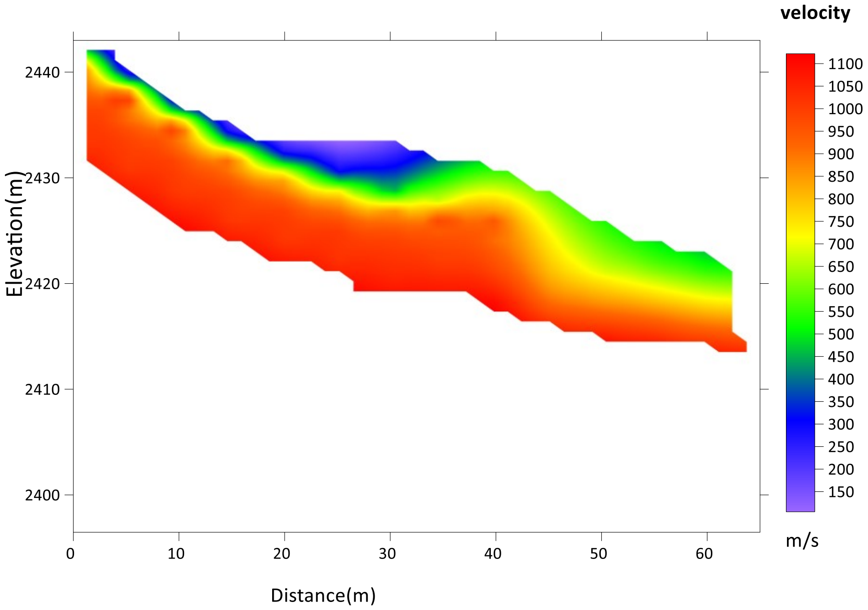


Adi Mesnu Landslide Profile 2

Key for Adi mesnu landslide profile 2

200-600 m/s- Accumulated unconsolidated material

650-1000 m/s -weathered limstone

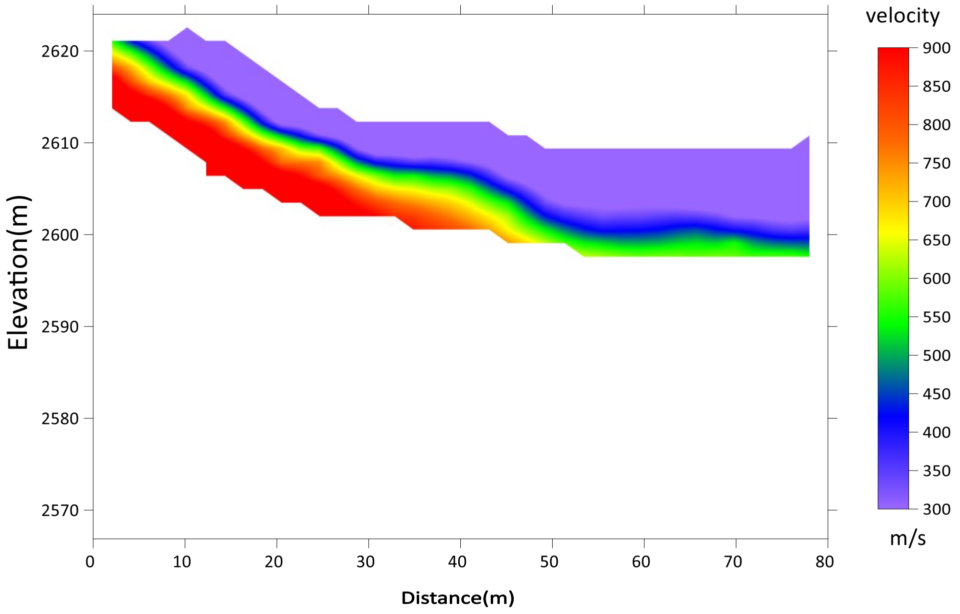


Adi Mesnu Landslide profile 3

<u>Key for Adi mesnu landslide profile 3</u>

150-600 m/s- Accumulated unconsolidated material

650-1100 m/s -weathered limstone

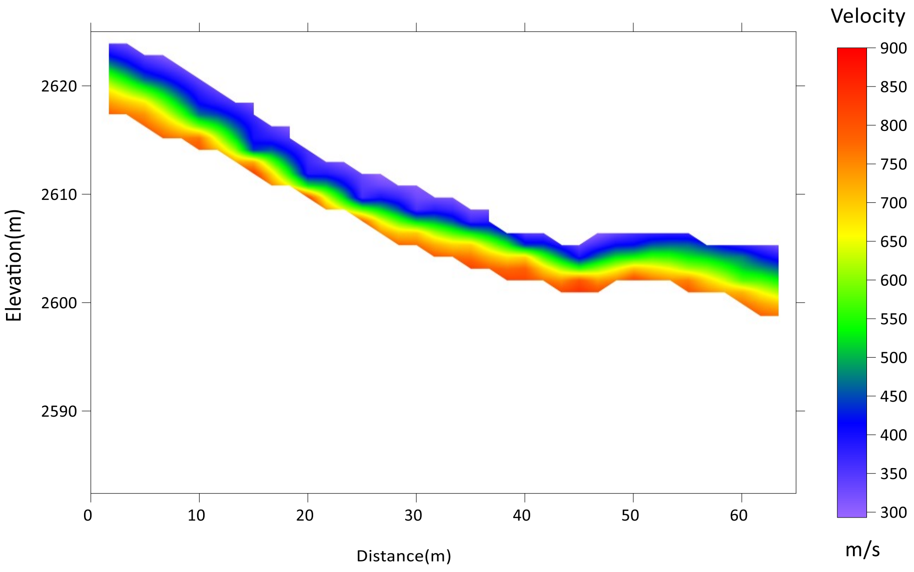


Hagere Selam landslide Profile 1

Key for Hagere Selam landslide profile 1

300-600 m/s- Active sliding masss of unconsolidated material

650-900 m/s –weathred shale and limestone

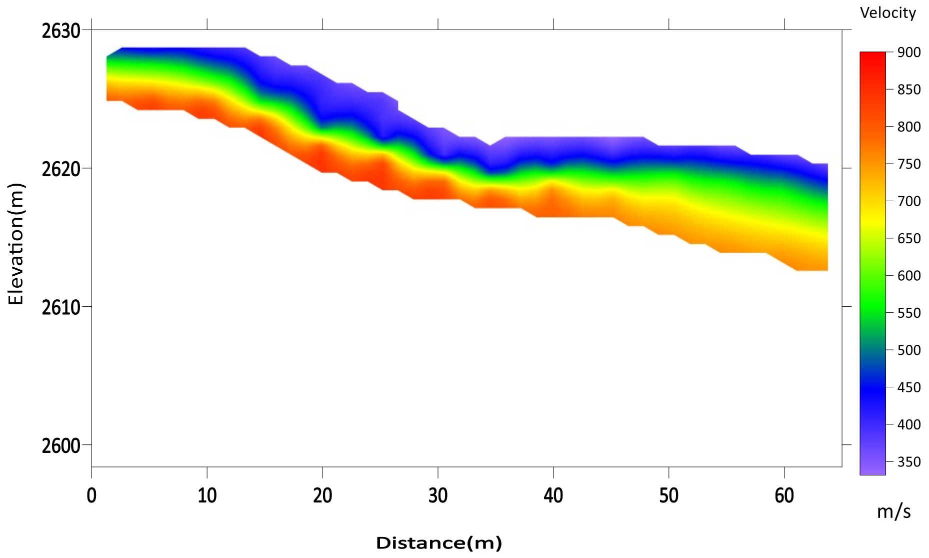


Hagere Selam Landslide Profile 2

Key for Hagere Selam landslide profile 2

300-600 m/s- Active sliding masss of unconsolidated material

650-900 m/s –weathred shale and limestone

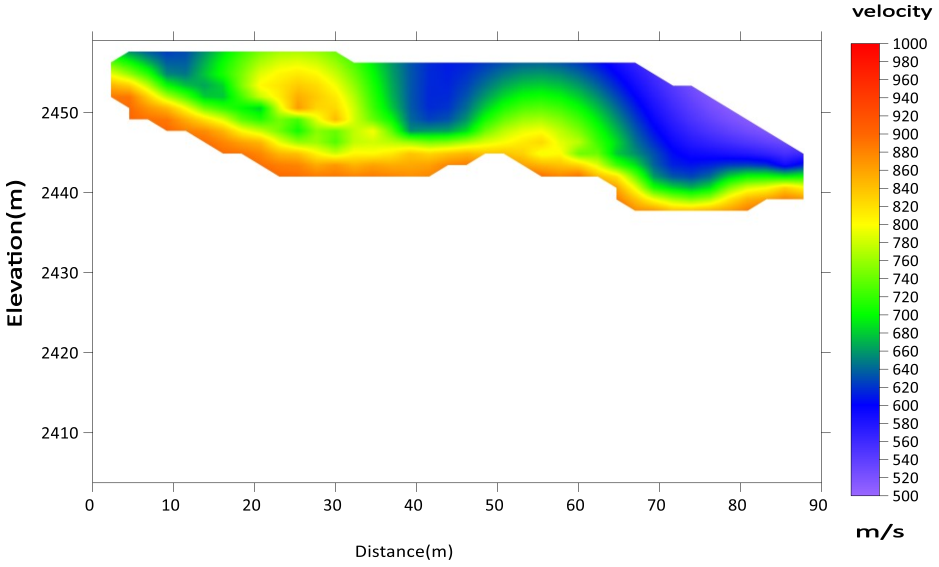


Hagere Selam Landslide Profile 3

Key for Hagere Selam landslide profile 3

300-600 m/s- Active sliding masss of unconsolidated material

650-900 m/s –weathered limestone and shale

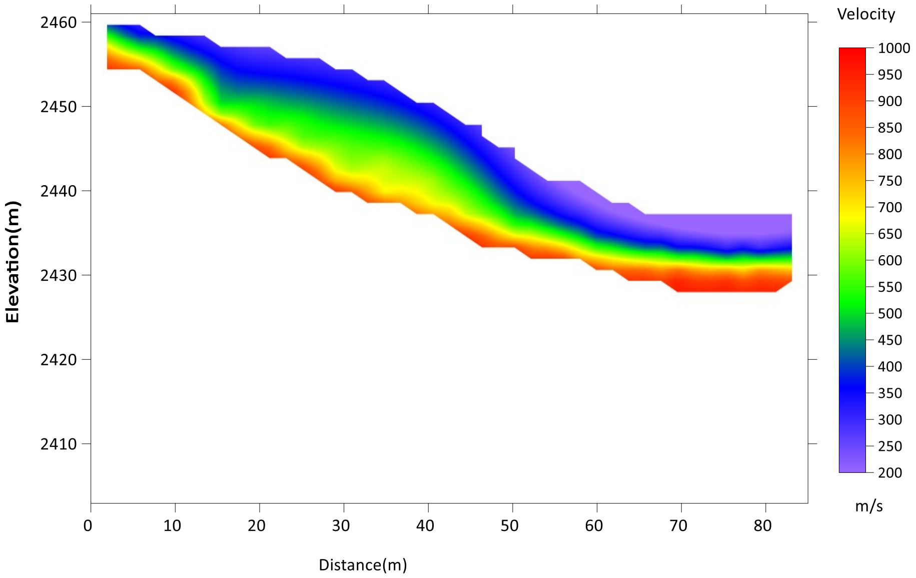


Hala Landslide profille 1

Key for Hala landslide profile 1

500-720 m/s- Active sliding masss of unconsolidated material with road infill material

740-1000 m/s –weathered limestone intercaleted with marl

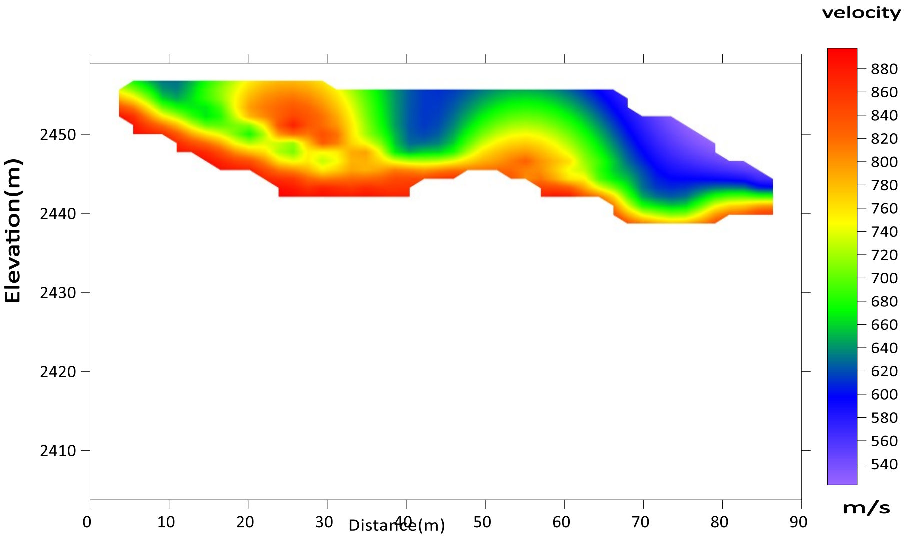


Hala Landslide Profile 2

<u>Key for Hala landslide profile 2</u>

200-600 m/s - Active sliding masss of unconsolidated material

650-1000 m/s –weathered limestone intercaleted with marl



Hala Landslide Profile 3

Key for Hala landslide profile 3

540-720 m/s- Active sliding masss of unconsolidated material with road infill material

740-1000 m/s –weathered limestone intercaleted with marl