Controlling Parameters and Failure Mechanisms of a Large-scale Landslide in Ethiopia

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Rainfall-triggered slope failures are common in different geological, topographical and geohydrological environments of the northern highlands of Ethiopia. The terrains underlain by Paleozoic glacial sediments are among those areas, which have been affected by shallow as well as deep-seated slope instability. From 1998 to 2002 alone, about 138 landslides (of various types and sizes) have been recorded in these terrains, among which is a large-scale landslide in a locality called "Hadish Adi" (about 5 km south of Feresmay town) (Figure 1).

This large-scale landslide (Figure 2) was reactivated on August 11, 2001, following heavy rainfall. The slope is believed to have failed, for the first time in August 1954, following a heavy rainfall (personal communication with local people). The reactivated landslide involved broad ranges of slope masses (including rock and soil), and had undergone a highly complex mechanism of failure. It destroyed 17 rural houses, two surface water reservoirs (ponds), and two hand-dug wells. The landslide had affected about 1.8 hectares of agricultural land, and caused damage to the natural environment. About 25 people were displaced from the landslide area, and more than 75 people still live in the area of high landslide risk.

According to various authors (5,15) slope failures are attributed to a number of influencing parameters. A clear understanding of the geological environment as well as proper evaluation of the geotechnical and geohydrological characteristics of soil and rock masses is the key for a slope stability assessment (5, 6, 7, 8, 9). To understand the causes and mechanisms of failures, and to identify the most relevant influencing factors, detailed geological, geohydrological, and geotechnical investigations were carried out, which involved aerialphoto interpretation (10), surface mapping (1 : 5 000 scale), subsurface investigations (using test pits and trenches), in-situ hydraulic conductivity tests of soils, in-situ strength tests of rocks, and laboratory analyses of soils and rocks.

Einflussfaktoren und Versagensmechanismen für eine Massenbewegung in Äthiopien

Im nördlichen Hochland von Äthiopien lösen heftige Regenfälle häufig Massenbewegungen aus. In diesem Beitrag werden die Einflussfaktoren, die Versagensmechanismen und die möglichen Sanierungsmaßnahmen einer großen Massenbewegung im Norden von Äthiopien diskutiert. Im bearbeiteten Gebiet liegen harte Sandsteine und Basalte über weichen paläozoischen glazialen Tilliten und postglazialen Sedimenten. Die Sandsteine und Basalte weisen eine hohe Scherfestigkeit und sekundäre Durchlässigkeit auf, während die Tillite und postglazialen Sedimente geringe Festigkeit und geringe Durchlässigkeit aufweisen. Unkonsolidierte Ablagerungen unterschiedlicher Mächtigkeit und hydraulischer Eigenschaften formen den unteren Teil der Hänge. Entlang den Hängen können in Bezug zum Versagensmechanismus drei Zonen unterschieden werden: (1) Felsstürze und untergeordnet Felsgleitung, (2) großvolumige Felsgleitungen mit Schuttströmen und (3) seichte Schutt- und Bodenrutschungen. Das die kompetenten klüftigen Gesteine unterlagernde weiche, schwach durchlässige Gebirge und geohydrologische Verhältnisse, die einen Aufbau des Wasserdrucks im Hang ermöglichen, bestimmen die Stabilität. Zur Stabilisierung des Hangs werden Oberflächen- und Tiefendränagen vorgeschlagen. Die Wässer können für den Gebrauch in der Trockenzeit gespeichert werden, woraus sich ein sinnvoller Zusatznutzen der Maßnahmen ergibt.

The northern highlands of Ethiopia are frequently affected by rainfall-triggered slope failures. This paper discusses controlling parameters, failure mechanisms, and remedial measure options of a large-scale landslide in northern Ethiopia. The landslide affected area is characterized by hard rocks (sandstone and basalt units), which are underlain by soft rocks (Paleozoic glacial tillites and post-glacial sediments). The sandstone and basalt units are competent rocks with high secondary permeability and high shear strength, while the tillites and post-glacial sediments are incompetent rocks with low permeability and low shear strength. A fault strikes parallel to the longitudinal axis of the landslide. Unconsolidated deposits of variable thickness and hydraulic characteristics dominate the lower sections of the slopes.

Three major zones of instability have been identified along the slope profile: (1) Rockfalls and minor rock block slides, (2) Large-scale rockslides and associated debris slides, and (3) Shallow debris/earth slides. The stability of the slope is dominantly controlled by the presence of soft and impermeable rocks underlying the hard and jointed rocks, a geohydrological environment, which promotes water pressure build-up within the slope, and a steep slope that can mobilize adequate stress to promote failure. Surface as well as subsurface drainage of the slope, with the objective of stabilizing the slope and at the same time harvesting the water for multipurpose use is considered to be the most feasible option as a remedial measure.

Site characteristics

As indicated in Figure 3, the area is characterized by high topographical variability, with elevation ranging from 1 850 to 2 550 m above sea level. It is represented by mountains, which are interspersed by steep-sided valleys and numerous streams. The variation in topography, along with its wide range of rock types not only provides an impressive and varied landscape but also a variety of landslide hazards. The landslide affected area is represented by a concave slope shape.

Though there are no specific records of the climatic conditions for the landslide area, the region in general is represented by a semi-arid environment (12). The annual mean rainfall of the area (data from May Kenetal weather station, located 27 km south of the area at an altitude of 1 825 m above sea level, of the last 17 years) is about 700 mm. The northern highlands of Ethiopia in general (11, 13) and the landslide area in particular are affected by active surface processes such as erosion and gullying. Most of the drainage lines in the lower sections of the hillslopes are associated with active erosion and gullying. It is not uncommon to find deeply cut streams (up to 10 m deep and 15 m wide) as a result of such processes. The western part of the area (dominated by steep slopes) is characterized by sparsely to moderately dense trees and grass, while the central and eastern parts of the area are farmlands with sparse vegetation cover.

Geology and geohydrology of the area

Geology

The major rock and soil types in the area (Figure 4) include metamorphic rocks, Enticho sandstone, Paleozoic glacial tillites, post-glacial sediments, Adigrat sandstone, basalt (upper and lower units), volcanic plugs, and unconsolidated deposits (debris and residual soils).

The metamorphic rocks are heterogenous units that include metavolcanics and metasediments. The metavolcanics are green to purple coloured, fine to medium grained, jointed schist (block sizes varying from 0.03 to 0.85 m³) with intermediate and basic lavas, greywacke, agglomerate, and rhyolite inclusions. The metasediments are black/graphitic or variegated coloured, fine grained, highly foliated (spacing 0.05 to 0.2 m), jointed (spacing 0.15 to 0.75 m) slates/phyllites with some calcareous sediments.

The Enticho sandstone is grey to white coloured, fine to medium grained, horizontally bedded (thickness 0.7 to 1.8 m), jointed (spacing 0.5 to 3.5 m) sandstone with sand-silt matrix and poorly sorted pebbles and boulders (up to 50 cm diameter). The block size of the Enticho sandstone varies from 0.15 to 5.5 m³. In some cases, joints with aperture up to 10 cm and continuity up to 5 m were observed.
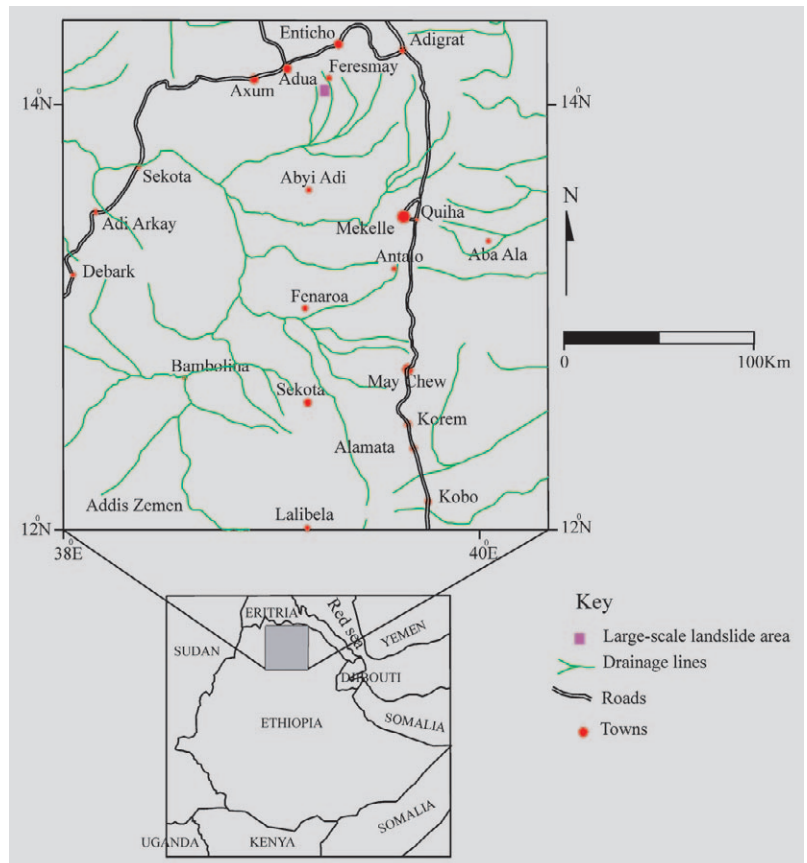

Fig. 1 Location map of the large-scale landslide.
Bild 1 Übersichtsplan mit Lage der Massenbewegung.

The (Paleozoic glacial) tillites are represented by grey to black sand-silt-clay matrix, interbedded with thin layers (thickness 0.05 to 0.15 m) of silty limestone, and with poorly sorted pebbles and boulders (up to 6 m diameter). Boulders in most cases are granite and basalt. The post-glacial sediments are dominated by grey to purple, well-laminated clay, silt and fine sand. In some cases these post-glacial sediments grade into poorly cemented, fine to medium grained, horizontally bedded (thickness 0.1 to 0.7 m), jointed sandstone (spacing 0.25 to 0.65 m) with block sizes varying between 0.005 to 0.2 m³. The tillites and post-glacial sediments display high variation in their lateral as well as vertical distribution.

Fig. 2 Front view of the large-scale landslide.
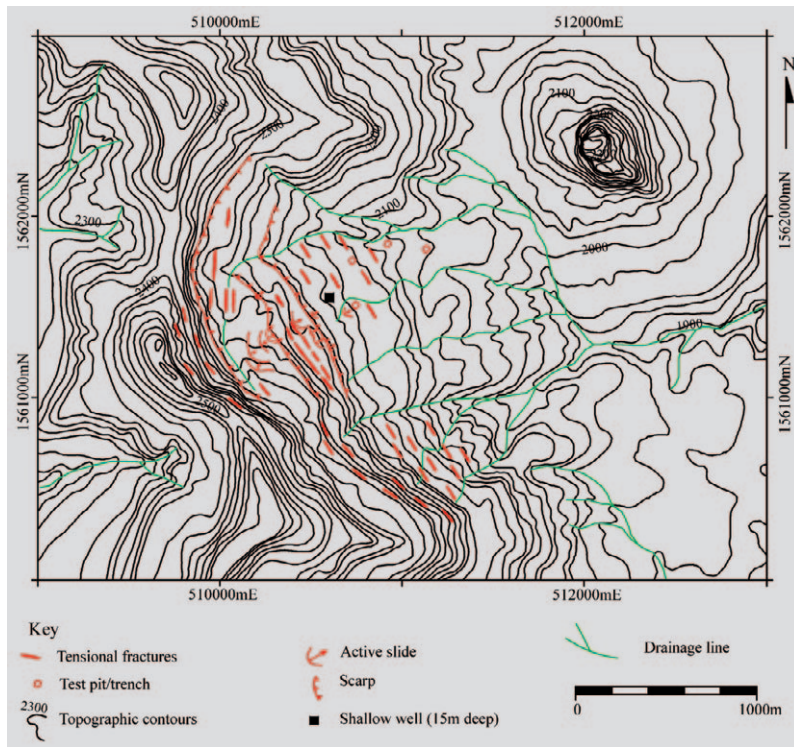*Bild 2 Frontalansicht des Gebiets der Massenbewegung.*

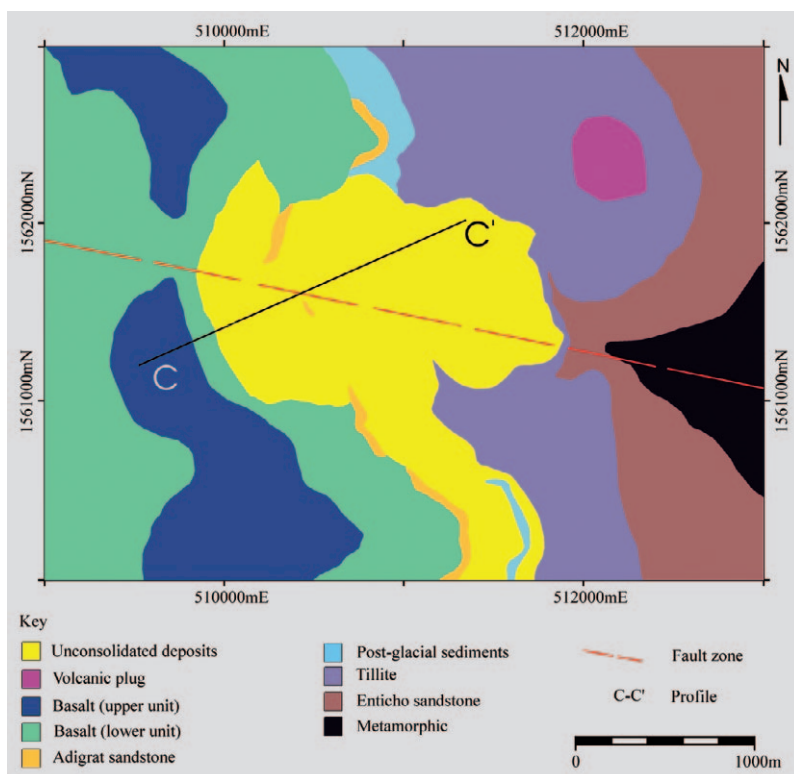**Fig. 3** Topography and landslide features.
Bild 3 Topographie mit eingetragenen Rissen und Rutschungen.

Fig. 4 Geology of the large-scale landslide area.
Bild 4 Geologische Übersicht des Gebiets der Massenbewegung.

The Adigrat sandstone consists of red to brown, medium to coarse-grained, slightly to moderately weathered, horizontally bedded (thickness 0.8 to 2.7 m), jointed sandstone (spacing 0.7 to 3.5 m) with block sizes varying between 0.8 and 12.5 m³. Most of the joints in these rocks are sub-vertical, and in many cases the sandstone cliffs exhibit tensional fractures with an opening up to 0.8 m.

The basalt units (upper and lower) are dark coloured, fine to coarse grained, and fractured with horizontal flows and vertical or sub-vertical joints. The lower basalt unit is more fractured (joint spacing 0.2 to 1.5 m), with characteristic block sizes ranging from 0.01 to 1.5 m³, and with intercalations of volcanic ash and lacustrine deposits. The upper unit consists of relatively widely spaced joints (0.3 to 2.3 m), with characteristic block sizes ranging from 0.2 to 2.5 m³. The volcanic ash and lacustrine deposits are horizontal layers with thickness ranging from 0.1 to 0.3 m, and are more frequent in the upper unit than in the lower basalt unit. Sub-vertical tensional fractures, which run parallel to the slope face with openings up to 0.5 m, are common in both the upper and lower basalt units.

The volcanic plugs are pale coloured, fine-grained alkaline igneous rocks, and consist of series of flows with jointing (spacing 0.8 to 3.7 m), with the characteristic block sizes ranging from 0.8 to 12.5 m³. These rocks are affected by sub-vertical to vertical tensional fractures (with openings up to 2.5 m).

Unconsolidated deposits, which include debris materials and residual soils, are common in the lower section of the slopes. The variation of their properties is high. The debris deposits are dominated by coarser materials (gravel, cobble, boulder) with a smaller amount (10 to 40 %) of fine materials (sand, silt, clay). The coarser materials originate from the rocks, which form the steep terrains up the slope. The residual soils are dominated by finer materials, which are derived from the post-glacial sediments, tillites, basalt, and sandstone. It was not possible distinguish between debris deposits and residual soils separately, thus they are considered and mapped as one unit "unconsolidated deposits". The area is affected by a fault/lineament, which strikes approximately E-W.

Geohydrology

The overall geohydrological condition of the landslide affected area was deduced from the distribution of rocks and soils, in-situ saturated hydraulic conductivity tests of soils, grain-size distribution analysis of soils, and discontinuity characterization of rocks. In order to get a better understanding of the hydrological processes and hence the flow of water within the slope, a geohydrological slope profile was developed (Figure 5). Five geohydrological zones have been identified along the slope profile.

Zone A

The upper and lower basalt units dominate this zone. The vertical/sub-vertical joints and tensional fractures create a favourable condition for rainwater percolation. In some areas, intercalations of volcanic ash/lacustrine deposits with low permeability within the basalt units are encouraging the emergence of springs in this zone during rainfall seasons. This section of the slope is generally acting as a recharge zone for surface as well as subsurface water flows to the down slope areas.

Fig. 5 Typical geohydrological slope profile (C-C').
Bild 5 Typisches geohydrologisches Profil (Schnitt C-C).
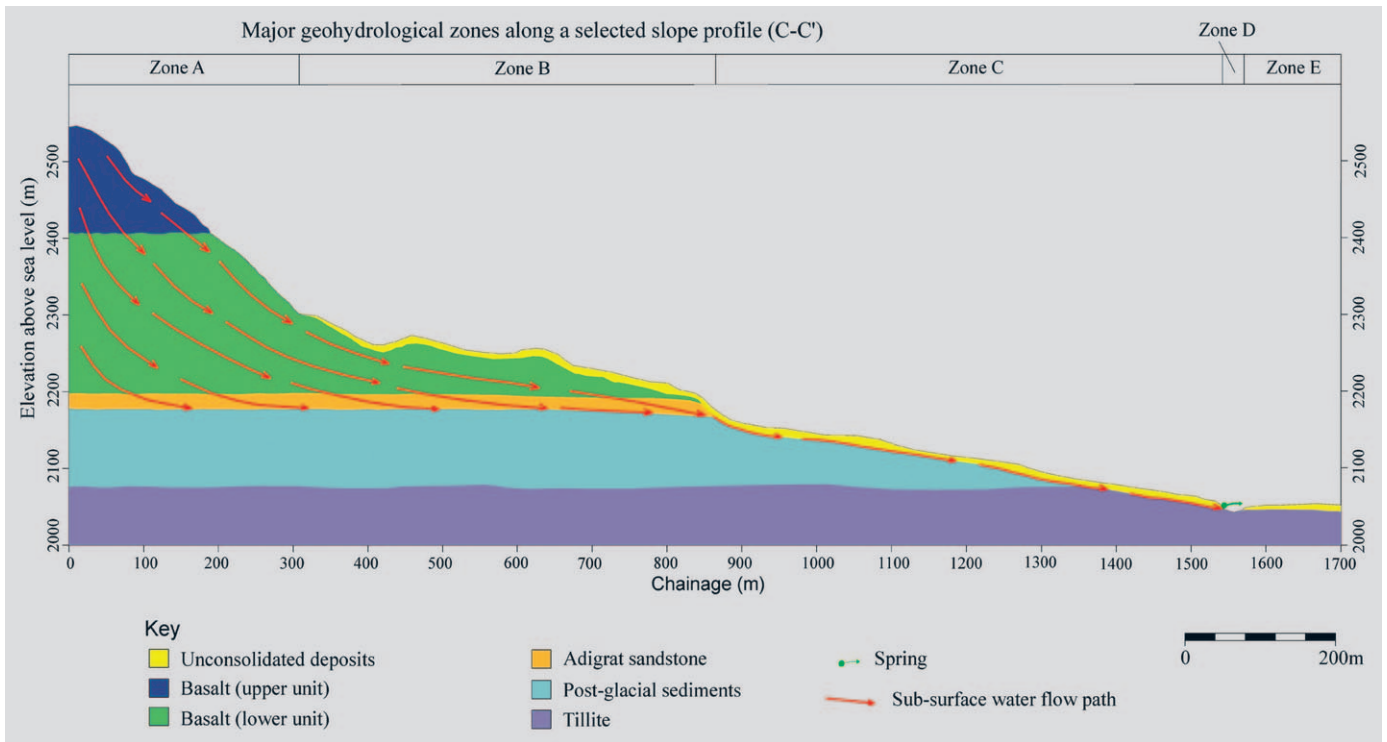
Zone B

Zone B is represented by sandstones and basalts (lower unit), which are underlain by post-glacial sediments. Shallow unconsolidated deposits cover the basalt and sandstone units. Subsurface investigations (Figure 6a) revealed that the unconsolidated materials have a thickness up to about 5 m and are underlain by a highly fractured and disturbed basalt unit.

This section has a hummocky topography, which is associated with series of tensional fractures with en echelon pattern. The tensional fractures capture large quantities of surface runoff. Depressions are common in this zone and have the potential to trap surface runoff and hence enhance groundwater recharge to the underlying mass. The absence of well-developed drainage lines in this zone suggests a high infiltration capacity of the rocks and unconsolidated deposits. Numerous springs and seepage zones emerge at the contact between the sandstone and the post-glacial sediments, indicating that the latter are acting as barriers. In general, this section of the slope is acting not only as a zone of rainwater percolation but also as an area of groundwater accumulation from the upper sections of the slope.

Zone C

This zone is dominated by unconsolidated deposits, which are underlain by moderately to highly weathered post-glacial sediments and tillites. Data from subsurface investigation (test pits and trenches) as well as from shallow groundwater wells indicate that the unconsolidated deposits have variable thickness, with maximum up to 15 m. A permeable zone (stony layer) was found at the interface between the unconsolidated deposits and the moderately to highly weathered bedrock (Figure 6b and 6c). To estimate the in-situ saturated hydraulic conductivity of the highly weathered post-glacial sediments and tillites, the inverse Auger-hole test method (1) was used. The highly weathered rocks have in-situ saturated hydraulic conductivity values that range from $1.5 \cdot 10^{-4}$ to $4.2 \cdot 10^{-6}$ m/s for the post-glacial sediments, and from $2.2 \cdot 10^{-5}$ to $5.4 \cdot 10^{-7}$ m/s for the tillites.

Typical vertical weathering profiles
(a) (b) (c)

Key
- Unconsolidated deposits
- Stony layer: gravel and cobble size materials
- Fractured basalt
- Moderately to highly weathered post-glacial sediments
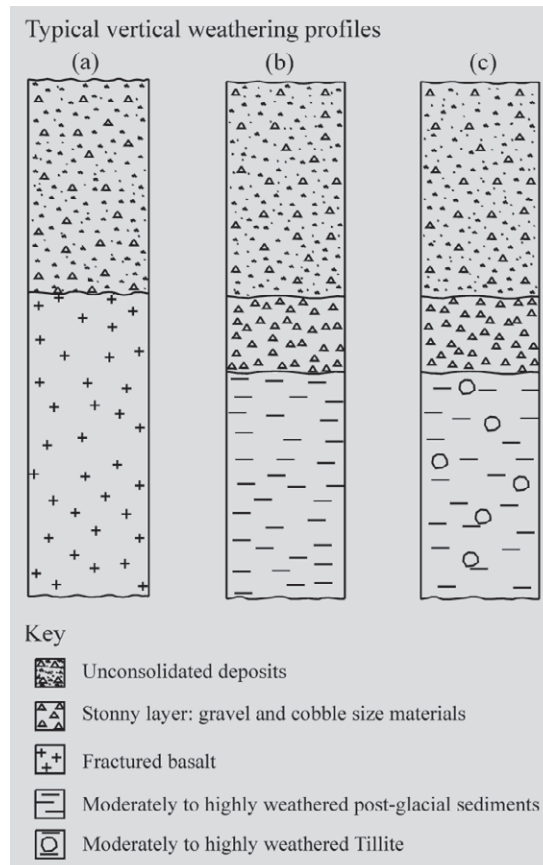- Moderately to highly weathered Tillite

Fig. 6 Typical vertical weathering profiles; (a) vertical profile in basalt unit; (b) vertical profile in post-glacial sediments; (c) vertical profile in Tillites.
Bild 6 Typische Verwitterungsprofile, (a) Basalt, (b) post-glaziale Sedimente, (c) Tillite.

Table 1 Geotechnical properties of rocks. n=number of tests. Schmidt Hammer Type L.
Tabelle 1 *Geotechnische Eigenschaften des Gebirges.*

Rock type	Unit weight [kN/m³] (moist)			UCS [MPa] (Schmidt hammer test)			Friction angle [°] (tilt test)		
	n	Range	Mean	n	Range	Mean	n	Range	Mean
Basalt (upper unit)	4	24-27	26	15	115-225	140	10	28-44	38
Basalt (lower unit)	8	25-29	27	28	130-235	165	35	30-46	36
Adigrat Sandstone	8	19-26	24	38	62-125	100	47	31-38	34
Enticho Sandstone	4	20-24	22	18	55-115	75	23	28-40	35
Metavolcanics	4	24-28	26	17	125-235	160	27	27-42	36
Metasediments	4	21-25	23	10	43-125	65	6	26-34	30

Table 2 Shear strength parameters of the soils (Direct shear test in drained condition, n=number of tests).
Tabelle 2 *Scherfestigkeitsparameter des Bodens.*

Soils derived from	Unit weight [kN/m³] (moist)			Cohesion [kN/m²] (Direct shear test)			Friction angle [°] (Direct shear test)		
	n	Range	Mean	n	Range	Mean	n	Range	Mean
Post-glacial sediments	5	20-25	22	4	7-15	12	4	21-27	24
Tillites	8	18-24	21	4	11-18	15	4	19-26	22
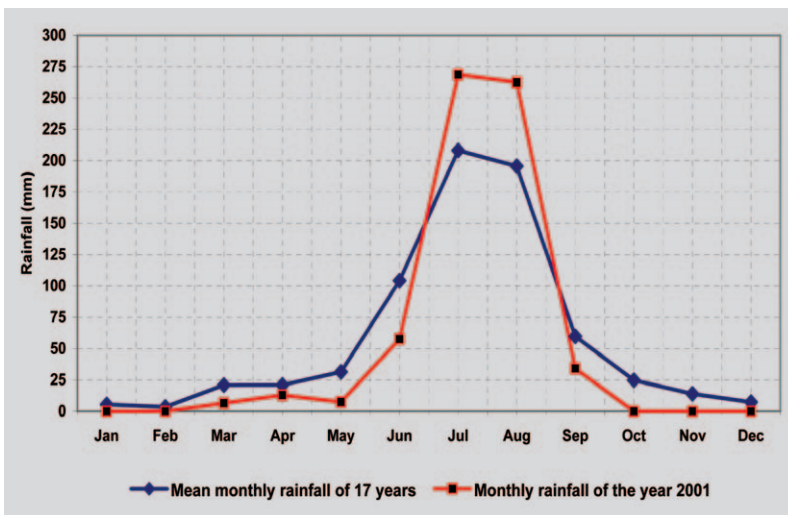
Fig. 7 Mean monthly rainfall of the area for the last 17 years (1967 to 2002) and monthly rainfall for 2001. Mean annual rainfall = 696 mm.
Bild 7 *Durchschnittlicher monatlicher Niederschlag über 17 Jahre und Niederschlag im Jahr 2001. Durchschnittlicher jährlicher Niederschlag = 696 mm.*
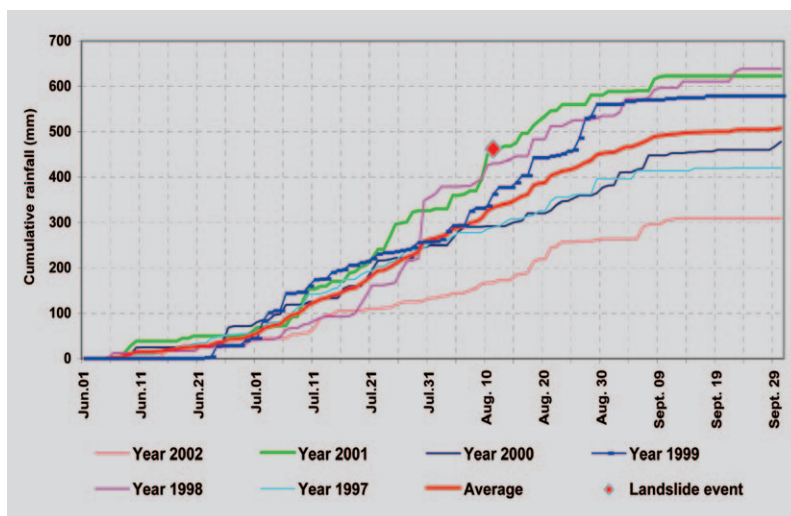

Fig. 8 Cumulative rainfall for the months June to September of the years 1997 to 2002; landslide event on August 11th 2001.
Bild 8 *Histogramm des Niederschlags in den Monaten Juni bis September von 1997 bis 2002; Reaktivierung der Massenbewegung am 11. August 2001.*

The permeable layer, found at the transition between the unconsolidated deposits and the underlying bedrock, is believed to have developed due to erosion of the fine components of the unconsolidated deposits, which then implies that rise in groundwater table within the slope (during heavy rainfalls) could promote subsurface erosion (piping), and hence contribute to the destabilization of the slope.

Zone D
This zone is the lower end of the old debris/earth slide, and is represented by a stream (10 m deep and 15 m wide). In the stream section, the thickness of the unconsolidated deposits reaches up to 9.5 m and is associated with active erosion and gullying. A spring, with a discharge of 1.5 l/min emerges at the contact between the unconsolidated deposits and the underlying weathered tillite.

Zone E
This zone is dominated by very shallow unconsolidated deposits (thickness less than 0.7 m) with relatively flat topography and with no features of seepage.

Geotechnical characteristics of rocks and soils

Characteristics of rocks
The engineering properties of the different rocks were estimated from field tests (Schmidt Hammer Rebound tests and tilt tests) and laboratory investigations. The post-glacial sediments and tillites in the area are moderately to highly weathered. A summary of the geotechnical properties of the rocks is given in Table 1.

Characteristics of soils
Though the unconsolidated materials also include debris deposits, only the residual soils (derived from post-glacial sediments and tillites)

were considered for laboratory analysis. The laboratory tests include direct shear tests, grain size distribution analysis, and Atterberg tests. A summary of the strength parameters of the soils is given in Table 2. According to the Unified Soil Classification System (USCS) (14), the major soil groups include silty sand (SM), clayey sand (SC), inorganic clays of low to medium plasticity (CL), and inorganic silts and very fine sands with slight plasticity (ML).

The soils derived from tillites are dominated by silts and clays of variable plasticity. According to the Unified Soil Classification System (USCS), the main soil groups include inorganic clays of high plasticity (CH), inorganic clays of low to medium plasticity (CL), inorganic silts, fine sandy or silty soils of high plasticity (MH), inorganic silts and very fine sands with slight plasticity (ML).

Hydrological triggering of the landslide

Studies from different parts of the world on the relationship between rainfall and landslides (2, 3, 4) indicate that both antecedent rainfall and a critical intensity of rainfall are important factors in triggering landslides.

To find some relationship between rainfall and the "Hadish Adi" large-scale landslide, rainfall data from the May Kenetal weather station was used. The spatial variation in rainfall is not taken into account in the analysis because of the absence of other nearby weather stations. The main rainfall season is between June and September (Figure 7), with about 80 % of the annual rainfall occurring during this season. Figure 7 also shows that the rainfall intensity in the year 2001 was considerably above average in July and August.

The cumulative rainfall for the years 1997 to 2002 is shown in Figure 8. It can be noticed that the amount of rainfall in 2001 was close to the average of the other years until mid of July. Heavy rainfalls were recorded late in July and on August 9th and 10th, raising the cumulative rainfall considerably above the average. The landslide was reactivated on August 11th, 2001 as a reaction to the unusually high antecedent rainfall in the second half of July and the heavy rainfall on August 9th and 10th (80 mm over the last two days before the landslide).

To assess the groundwater response to rainfall, monthly measurements of the static water level of a 15 m shallow well, located at the lower section of the slope was used. Records of the static water level of the well were available only for the year 2000. In Figure 9 the monthly rainfall and the static water level in the well are plotted. It can be seen that the water level in the well stabilizes about two months after about two months of rainfall, and after that rapidly increases up to the surface. The drop down of the water level in the well also starts about two months after the peak rainfall. The strong drop between September and Oc-
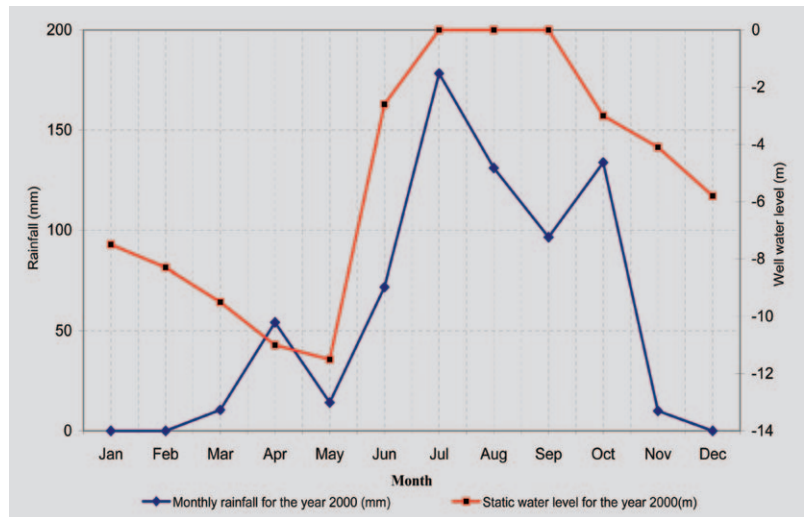

Fig. 9 Monthly rainfall and variation in static water level of a 15 m deep groundwater well of the year 2000; negative values indicate elevation below ground surface.
Bild 9 Monatlicher Niederschlag und Veränderung des Wasserspiegels in einem 15 m tiefen Brunnen; negative Werte beziehen sich auf den Wasserspiegel unterhalb des Brunnenrands.

tober is attributed to a highly permeable debris layer down to about 3 m from the surface.

In order to assess the surface water-groundwater interaction, water samples collected from shallow wells and springs were analysed. Results of the analyses reveal that the Total Dissolved Solids (TDS) values vary from 750 to
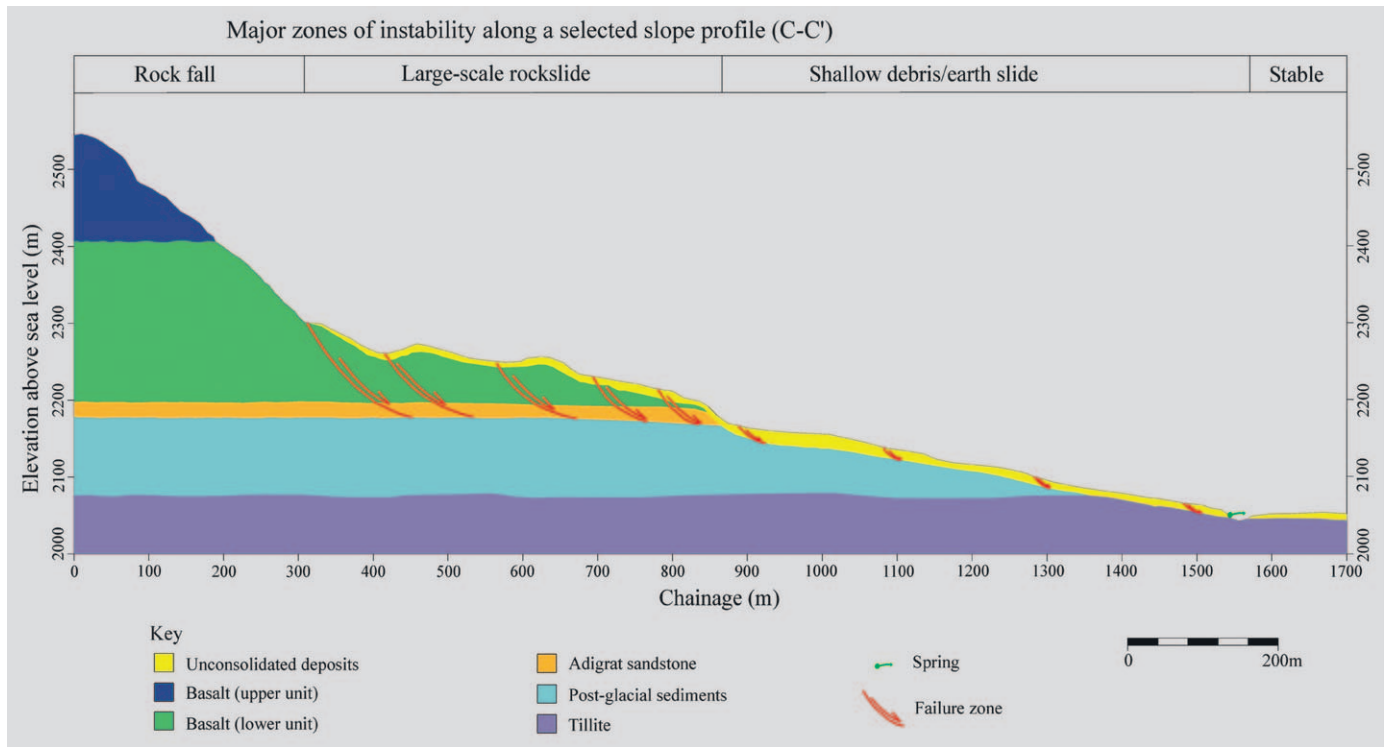
Fig. 10 Typical slope profile (C-C') which shows the major zones of instability.
Bild 10 *Typisches Hangprofil (C-C') mit Gleitbahnen.*

970 mg/l for spring water and from 780 to 1 050 mg/l for groundwater. Similar values of TDS for both spring and groundwater could indicate the same source of water, which in this case is subsurface water flow from the upper sections of the slope, recharged from rainfall.

Failure mechanisms

The failure mechanisms of the large-scale landslide was evaluated based on the:
⇨ Lateral as well as vertical distribution of the rocks and soils,
⇨ Geohydrological condition of the slope,
⇨ Geotechnical characteristics of soils and rocks,
⇨ Inventory of unstable slopes and features indicative of the mechanisms of failures, and
⇨ Kinematic analysis of discontinuities.
For a better understanding of the different failure mechanisms, a typical slope profile is devel-

Fig. 11 Side view of the upper part of the large-scale rockslide.
Bild 11 *Ansicht des oberen Teils der Massenbewegung, Blickrichtung Süden.*

oped (Figure 10). Three major zones of instability have been identified along the slope profile:
⇨ Rock fall and minor rock block slide,
⇨ Large-scale rockslide and associated debris slide, and
⇨ Shallow debris/earth slide.

Rock fall and minor rock block slide zone

Fractured basalt units dominate the upper section of the slope. Field investigations indicate that rockfalls occur in this zone, depositing debris onto the slope below. The basalt units consist of vertical to sub-vertical joints and open tensional fractures, separating columns of rock blocks and promoting toppling movement and minor rock block slide (planar sliding and wedge failures), which was confirmed by kinematic analyses.

The volcanic ash and lacustrine deposits, found as intercalations within the basalt units also promote sliding of basalt blocks. Failure in this section of the slope is therefore dominantly controlled by the discontinuities within the basalt rocks, with some influence by the volcanic ash/lacustrine deposits. The tensional fractures within the slope masses are signs of deep-seated instability, and are considered to be associated with:
⇨ The long-term ductile deformation of the soft rocks (post-glacial sediments), which are underlying the hard rocks, and
⇨ Stress release due to the large-scale rockslide at the slope below.

Large-scale rockslide and associated debris slide zone

The middle section of the slope consists of jointed hard rocks (sandstone and basalt), which are underlain by moderately to highly weathered

soft rocks (post-glacial sediments). Unconsolidated materials of variable thickness (not exceeding 5 m) cover these hard rocks. As compared to the dimension of the unstable slope, the joints within the hard rocks are short and less prominent, and the intact rock blocks are very small and not interlocked. These hard rocks are considered as highly jointed rock masses, although the characteristic block size of the sandstone is a little bigger than that of the basalt unit.

Large-scale rockslides and associated debris slides are the major types of failures in this zone (Figures 11 and 12). Series of tensional cracks (Figure 13) of an en echelon type were found in this section of the slope. Bulging of ground surface in some areas and settlement/subsidence in other areas were also observed in the field.

Water pressure build-up within the jointed rock mass, due to high antecedent and daily rainfall, is believed to have played a major role in triggering the slide. In addition to generating seepage force, water is believed to have contributed to the destabilization of the slope through subsurface erosion (piping) and lubrication of the weathered soft rocks (post-glacial sediments).

It is likely that failure initiated at the toe, which in turn lead to load transfer to adjacent areas. In the early stages of failure, the slope near the toe (mainly dominated by the sandstone) could also have moved more or less as a rigid block over the soft rocks. Progressive failure is believed to have involved first failure along pre-existing discontinuities but failure through the intact rock bridges between pre-existing joints could also have contributed to the failure development. By the movement the intact rock pieces within the slope have undergone translation, rotation, tilting or crushing. Several highly complex secondary modes of failures have occurred within the whole mass. From field observation the dominant mode of failure is a quasi-rotational shear failure, with an overall failure surface following a curved path. It is believed that the failure surface is formed by the discontinuities within the hard rocks. The soft rocks, and the discontinuities and intact rock bridges within the sandstone and basalt units dominantly control the instability in this section of the slope.

Shallow debris/earth slide zone

Unconsolidated deposits, underlain by soft rocks dominate the lower section of the slope. The major types of failures in this zone are debris/earth slides. The dominant modes of failures are translational slides, in limited areas combined with other failure modes where adequate thickness of unconsolidated materials exists to generate deeper failure surfaces. The main detachment zone is found to be at the interface between the unconsolidated deposits and the underlying moderately to highly weathered soft rocks.

The presence of a permeable zone at the interface between the moderately to highly weath-

Fig. 12 Side view of the lower part of the large-scale rockslide.
Bild 12 Ansicht des unteren Teils der Massenbewegung, Blickrichtung Süden.

ered soft rocks and the overlying unconsolidated materials is creating a suitable geohydrological environment for water pressure build-up within the unconsolidated deposits during heavy rainfalls. The association of debris/earth slides with drainage lines which are affected by active erosion and gullying indicate that such surface processes have contributed to the destabilization of the lower section of the slope through removal of materials that provided support at the toe.

Remedial measure options – possible models

Slope stabilization methods generally aim at reducing driving forces, increasing resisting forces, or both. Driving forces can be reduced by excava-

Fig. 13 Tensional cracks of en echelon type (up to 0.5 m wide) at the middle section of the large-scale landslide.
Bild 13 Bis zu 50 cm offene Spalten im mittleren Teil der Massenbewegung.

tion of materials from the appropriate part of the unstable ground or by drainage of water within the unstable zone. Increasing the resisting forces of a slope generally involves provision of additional support, which often works for small-scale slopes. In the case of the large-scale landslide at "Hadish Adi", with almost no sensitive engineering structures in the area, drainage is considered to be the most feasible remedial measure, as it reduces the destabilizing seepage force on the slope as well as the risk of erosion and piping of the materials within the slope. Even then, adopting costly drainage systems may not be feasible unless other additional socio-economic benefits are involved. Since the landslide affected area is among those with shortage of water during the dry seasons, but with some potential for small-scale irrigation, it is advisable to adopt "drainage based water harvesting".

The harvested water could be used for various purposes including water supply for the rural community and small-scale irrigation at the down slope area. This approach could improve not only the stability of the slope, but also the economic life of the local community. The proposed remedial measure option involves the provision of:

⇨ Surface drainage systems at the upper and middle sections of the slopes, and subsurface drainage systems using shallow large-diameter relief wells at the lower sections of the slope, with some horizontal drains mainly at the contact between the Adigrat sandstone and the post-glacial sediments,
⇨ Free flow canals,
⇨ Surface reservoirs (mainly ponds) at the lower sections of the slopes.

The streams at the lower sections of the slopes are associated with active erosion and gullying. It is possible that further erosion and gullying could contribute to the destabilization of the slope. It is therefore advisable to undertake comprehensive soil conservation measures to minimize stream erosion and gullying in the area in general and in the lower sections of the slopes in particular.

Discussion and conclusion

The presence of fractured basalt units at the upper section of the slope is enhancing rainwater percolation into the middle section of the slope. The middle section of the slope, which is dominated by fractured basalt and sandstone units, is acting as a temporary groundwater reservoir. The underlying impermeable rocks are acting as barriers for the vertical percolation of water, thus promoting lateral flow of water parallel to the slope surface. The unconsolidated deposits at the lower section of the slope, due to their relatively low permeability are retarding drainage and hence contributing to the water pressure build-up within the slope during heavy rainfall.

The concave shape of the terrain is enhancing the convergence of groundwater flow into the landslide area.

The relationship between rainfall and landslide event indicates that deep-seated failures prevail after a longer period of rainfall. Since it takes several weeks with considerable amount of rainfall to cause rise in groundwater table within the slope, the highest groundwater levels and consequently landslide event could be expected in the second or third month of the rainy season. For the triggering of landslides with deeper slip surfaces, the intensity and duration of one single event is of minor importance. Rainfall intensity alone could be an issue for shallow landslides, but not for very large deep-seated failures. In this case the total amount is much more relevant than high intensity rainfall. With the widespread and deep fissures, which drain rainfall to the lower impermeable stratum, only a very heavy rainfall could trigger a landslide. Hence a combination of high antecedent rainfall and high intensity of rainfall is more important. Concave hollows are found to be more susceptible for groundwater triggered landslides since groundwater levels are relatively high due to convergence of flow lines in such terrains.

Though triggered by rainfall, the landslide is believed to have been affected by various factors, which include long-term as well as short-term processes. The vertical tensional fractures within the hard rocks (sandstone and basalt units) are considered to be associated with long-term ductile deformation of the underlying soft rocks. Complex interaction of processes such as the lubrication of the soft rocks, weathering, and subsurface erosion (piping) are all considered to have contributed to the long-term processes. The stability of the large-scale landslide is dominantly controlled by the following major factors:

⇨ The presence of hard, competent, and permeable rocks underlain by soft, incompetent, and impermeable rocks,
⇨ A geohydrological environment which promotes water pressure build-up, and
⇨ A steep slope, which can mobilize adequate stress to promote failure.

Surface and subsurface drainage of the slope is considered to be the most feasible remedial measure option, with twofold objectives:

⇨ Stabilizing the slope, and
⇨ Harvesting the water for multi purpose use.

The scarcity of water during dry seasons and the excess water during rainfall periods makes it feasible to adopt such remedial measures as a general mitigation strategy in other parts of the northern highlands of Ethiopia where similar conditions exist. Active erosion and gullying at the lower sections of the slopes are considered to contribute to the destabilization of the slope. It is therefore advisable to adopt proper soil conservation measures so as to minimize erosion and gullying at the lower sections of the slopes.

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