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Loess failure in northeast Afghanistan

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Slope failure, Landslide, Debris slide/flow, Rockfall/slide, Rock glacier, Slope-failure complex

Abstract
Mass movements in northeastern Afghanistan include large-scale rockslides and complex slope failures, as well as failures in loess. The loess region in northeastern Afghanistan occurs in the Badakhshan and Takhar provinces and was likely created by dust blown to the east from the Karakum Desert and the alluvial plains of northern Afghanistan. This loessic dust was deposited against the Hindu Kush mountain range which rises up along the eastern half of Afghanistan as a result of transpressional tectonism. It overlies less permeable crystalline and sedimentary bedrocks such as Triassic granite, Proterozoic gneiss, and Miocene and Pliocene clastics in the area with the largest concentration of slope failures. Thirty-four loess slides and flows were mapped and analyzed using remote satellite imagery over digital elevation models on Google Earth™. This source enabled location, classification, and measurement of failures. Findings revealed that most failed slopes faced north, west, and northwest. This trend can be explained possibly as different moisture contents resulting from the primarily westerly wind direction, which may cause more precipitation to be deposited on west-facing slopes, and sun position during the hottest part of the day. Additionally, the easterly rising Hindu Kush range may cause more slope area to face west in the study region. Other contributing factors could be the very high seismicity of the area, which may cause rapid dry fluidized loess flows, and landscape modification by humans. Several...
loess slope failures appear to be generated by water concentration through irrigation ditches and possible rutted tire tracks, which can create tunneling between the loess and its less permeable bedrock. Causes and effects of loess failure in Afghanistan need to be investigated in more depth. Further study may lead to the adoption of more sustainable and safe farming practices and more informed housing locations, which may prevent loss of property, crop, and transport routes.
Introduction

As well as the larger rock slides and rock slide complexes noted by Shroder et al. (in press) there are categories of fine-grained mass movement in northeastern Afghanistan that occur where either water or seismic acceleration are the primary causes of slope failure. Of particular interest are the plentiful deposits of wind-blown dust that accumulate as loess blankets over pre-existing topography, particularly on top of crystalline or other bedrock of lesser permeability. Because of the nature of its slow accumulation, as the dust grains of fine silts and clays settle out of air-borne suspension down onto grass blades and other shrubby vegetation typical of the steppes of Afghanistan, a so-called ‘card-house’ matrix of loose loess grains is established. These card-house matrices are particularly subject to differential compaction and settling, to cracking when dry, and to piping, wherein larger connected openings are developed down into the ground as the loess grains are physically transported by water running downward into cracks and pipes. This commonly sets up a situation wherein water infiltrates the loesses, either as a function of the natural porosity and permeability of the loess, or where water infiltration is accelerated into cracks and pipes, all of which contributes to instability of the loess and results in slope failures. Seismic accelerations similarly can shake the loess so that the loose matrix collapses catastrophically and the dry loess is fluidized to flow outward and downward as a powdery mass moving under gravitational control alone. Loess slides and loess flows are special kinds of earth-slides or earth flows that occur in many places in Afghanistan. It is presumed on the basis of observations made elsewhere that velocities of such slope failures can be highly variable, from rapid to perhaps largely imperceptible creep.

It is the purpose of this paper to locate and describe multiple mass movements in the loess area of northeastern Afghanistan, in order to better understand distributions and primary causes of loess-slope failure in this region. By documenting these failures it is hoped that areas at increased risk for this type of fine-grained mass movement will be identified, and primary causes determined, in hopes of achieving greater safety and functionality and promoting continued development in this impoverished, subsistence based area.
Methodology

High resolution satellite imagery draped over a Digital Elevation Model (SIODEM) in the form of Google Earth™, which implements Shuttle Radar Topography Mission (SRTM) DEM data from NASA to create a synthetic topography, was used to locate loess failures and investigate the surrounding areas. Coordinates gained from Google Earth™ were applied to Soviet topographical maps at a scale of 1:250,000 to discover the underlying bedrock, although care had to be taken with variable lithologic designations, for example because metasedimentary rocks in many places were referred to by sedimentary rock names (e.g. siltstone instead of argillite; shale instead of slate; sandstone instead of quartzite, etc.) Bohannon and Stoeser, 2005; Desio, 1975). Other data sources were USGS maps and reports, as well as declassified CIA maps (Lindsay et al., 2005; Stoesser, 2005; Ruleman et al., 2007; US CIA, 2008).

Results: loess slope failures

Loess regions are commonly characterized by mass wasting, which generally occurs as loess flows or loess slides that can be dry or wet, and fast or slow. The speed, size, and type of loess-slope failure depend, among other things, on the structure and amount of moisture in the loess, the type (composition) of the affected materials, and the slope of the underlying bedrock beneath the loess (Derbyshire et al., 2000).

Loess slope-failure processes

Many mechanisms of mobilization occur, as do many different types of loess failure; organization schemes established by geologists and engineers focus variously on content and composition of the movement mass, location of the failure plane, or mobilization and type of movement. The latter types of classification focus on mobilization and type of movement so that broadly, movement can be seen to be caused by saturation and liquefaction, fluidization, hydro-consolidation, and progressive failure or loess “creep”.
Saturation and liquefaction

Though loess can be quite stable and cohesive when dry (as when Derbyshire et al. (1994) cited a functional bridge cut into loess near Lanzhou, China), it is subject to failure when saturated. Where wet, loess has a relatively low shear strength and a thick clayey consistency like that of toothpaste, and after reaching a certain saturation level it loses the ability to support itself (Bettis et al., 1986). Pye (1995) listed several reasons for this: (1) water dissolving or deforming salts, carbonates, and other framework materials; (2) reducing grain friction; (3) dissolving clay pellets from the matrix; and/or (4) deforming clay “bridges” between grains. In addition, water adds load weight to the loess structure, increasing downward pressure (Derbyshire et al., 2000).

In many places, loess stays fairly dry and stable because of relatively low precipitation, exposure to sun and wind (evaporation), and steep slopes (Bettis et al., 1986). However, in areas that undergo heavy rain or flooding or in latitudes that experience monsoons, catastrophic loess-slope failure can be a significant problem. Loess can mobilize as a mudflow or a rapid wet debris flow on the surface, or, if saturated along the basal layers (by piping or an impermeable bedrock contact), can form a “skating surface” for slump-block slope failure and landslides (Bettis et al., 1986). Failure is especially likely after several days of torrential downpours. Many such catastrophic landslides and mud flows have occurred in the Gansu Loess Plateau region of China, which receives up to 60% of its annual rainfall in the monsoonal months of August and September (Derbyshire et al., 2000).

Dry fluidization

Loess can move rapidly and catastrophically when dry, in an event variously referred to as dry fluidization, soil liquefaction, rapid soil flow, or loess powder flow (Zhang and Wang, 2007). These mass movements can be triggered by high-magnitude seismicity, which causes the porous, card-house matrix of the loess to collapse and fluidize. In tectonically active earthquake zones, such as the China Loess Plateau and along the Hindu Kush loess region in Afghanistan, this can be the primary trigger for
mass movement (Zhang and Wang, 2007). In a study done in China, Zhang and Wang (2007) found that these slides generally occurred on gentle, concave slopes of <15°, in contrast to saturation-induced landslides, which generally occur on steeper slopes.

Landslides mobilized by earthquakes, whether in loess or in a more stable sedimentary rock, are typically rotational, characteristically large in volume and scale, high-mobility, and can be very damaging (Derbyshire et al., 2000). In the Haiyuan earthquake of 1920 in the Chinese loess region, an estimated 100,000–180,000 people were killed by such earthquake-mobilized landslides (Zhang and Wang, 2007; Derbyshire et al., 2000).

**Hydroconsolidation**

Loess can collapse rapidly due to overburdening at certain critical moisture contents (Derbyshire et al., 1994). If overloaded, the loess will eventually collapse and settle, reducing pore space (Bettis et al., 1986). Moisture decreases the load strength of loess; Miller (1964) noted that “wet” loess, described as greater than 20% moisture, settles under light loads under 70,307 kg/m² (100 psi), whereas “dry” loess (less than 10% moisture) can hold heavier loads over 70,307 kg/m². Not all loess has the same potential for collapse. Younger loess is in general more collapsible and behaves plastically. Older loess tends to be dense and brittle, and usually has a greater bearing strength than overlying (younger) loess; it is less collapsible (Derbyshire et al., 2000; Miller, 1964). In China, engineering codes were instituted for buildings in areas with “collapsible loess”. The susceptibility of the area to collapse is calculated using the heights of the loess under normal conditions, under reduced pore space (under pressure), and when saturated and under pressure (Derbyshire et al., 1994).

**Loess “creep” or progressive failure**

Loess slope failures are not necessarily always catastrophic. In a process that Derbyshire et al. (1994) called progressive failure, the loess slope is gradually weakened by groundwater, which removes soluble salts and shifts particles. Stresses slowly transfer, and the loess readjusts, deforming and creeping downhill. This type of movement can produce step-like features along the failure plane called “teracettes” or
“catsteps” and arcuate cracks (crown cracks) at the crest of loess slopes (Derbyshire et al., 1994; Bettis et al., 1986). Such landforms are common in Afghanistan. Though loess appears to deform plasticly for awhile, Derbyshire et al. (1994) warned that eventually, the weakened loess exceeds a weathering threshold or is triggered externally, causing rapid slope failure.

Mass movements variously occur by failure at the bedrock or paleosol contact, failure entirely within loess, or at bedding planes or joints (mixed landslides). Derbyshire et al. (2000) summarized a classification system using the composition of the slide mass and the location of the failure plane that is relevant to loess failures in Afghanistan, although too reliant upon direct field observation to make direct comparison or complete classification possible:

1. **Bedrock-contact landslides** – These are the most common type of landslide involving loess (Derbyshire et al., 2000) and occur where rainfall filtering through loess meets a impermeable bedrock; the water then moves along the bedrock, saturating the layer of loess in contact with the bedrock, and causing slope failure (Fig. 2). This failure type can be compounded by tunneling in the basal layers. If the bedrock is jointed or otherwise permeable, the loess tends to be more stable.

2. **Paleosol contact landslides** – These occur where loess is in contact with a finer-grained, more compact paleosol. This is much the same as bedrock-contact landslides, in that the paleosol deflects percolating rainfall, leading to the formation of pipe systems. The soil and the basal loess layer are both saturated and weakened, leading to slope failure.

3. **Mixed landslides** – These occur where a layer of mudstone or clay located between the loess blanket and the underlying bedrock or within the bedrock causes slope failure. Generally, failure is along bedding planes or joints in the bedrock, and movement is relatively slow and short-distance.

4. **Landslides entirely within Loess** – Landslides involving only loess are somewhat uncommon in dry regions (Derbyshire et al., 2000). Movement can be the result of weakened cement bonds by dissolution or moisture, gravitational forces inducing failure at joints, or in areas where removal of material at the toe of a loess
slope has occurred.

Fig. 1. Index map of study area of northeast Afghanistan shows surrounding region and major fault lines in study area, with loess failures indicated on the inset.

**Northeast Afghanistan loess areas**

The Afghanistan loess regions of the northeast occur in a belt located on the western side of the Hindu Kush mountain range in northern Afghanistan (Fig. 1). This location reflects a generally westerly paleo-wind direction, which probably allowed deflation of dust blown out of: (1) the arid southern regions of the Karakum Desert of Turkmenistan and neighboring Uzbekistan and Tajikistan; and (2) the extensive alluvial plains of the Amu Darya river system of the north border of Afghanistan; and (3) the alluvial plains of northern Afghanistan, all to be deposited against the higher elevations in Afghanistan. This area is very tectonically active, with major transpressional fault lines (Chaman-Panjshir-Central Badakhshan fault system) running through the eastern half of Afghanistan, with branches extending into the north and
south-west regions of Afghanistan. Particularly close to the study area are the Darvaz and Henjevan faults (Fig. 3).

![Diagram of typical loess draped over crystalline bedrock in northeast Afghanistan. Microscopic to mesoscopic (connected pore spaces to joints and fissures) routes of water infiltration shown on right are commonly expressed over time through elutriation of fine clastics as megascopic pipes and tunnels that can be meters in diameter and highly conducive to subsequent ground failure and loess mass movement.](image)

Google Earth™ was used to locate loess mass movements in this region, which are recognizable from high resolution satellite imagery. Thirty-four significant failures were located and explored using this method, although it must be noted that considerably more exist. While difficult to classify in detail without field examination, several things can be noted about the movements using this technology. The first is the general location of the movements in relation to topography, river valleys, fault lines, and earthquake epicenters. Another is location relative cities, road networks, and cultivated areas. The satellite imagery also gives a rough estimate of the size of the failure, which can be classified as small to moderate relative to the larger slope failure complexes in Badakhshan. The ability to rotate and change the angle, direction, and height of the view perspective of the imagery draped across the underlying digital topography enabled detection and classification of the loess failures.
Fig. 3. Seismotectonic map of Afghanistan. Afghanistan is an accretion of several active plates, and there are numerous faults throughout the country. The northeastern area of Afghanistan is seismically active, in part as a result of the very active transpressional Chaman fault and the smaller Central Badakhshan, Darvaz and Henjvan faults, which are a result of the northward relative movement of the Indo-Australian tectonic plate (3–4 cm/year.) past the Eurasian (1.3 cm/year.) plate. The Darvaz, Central Badakhshan, and Chaman faults are indicated by DV, CB, and CF, respectively. After Wheeler and Rukstales (2007) and wheeler et al., (2005).

Most of the loess slope failures occur in one fairly small area bridging Badakhshan and Takhar provinces in northeast Afghanistan. This area corresponds to a strongly active seismic region with a heavy concentration of historical earthquake epicenters and a high “seismic hazard”, based on the level of shaking expected in the next 50 years (Crone, 2007). Loess slope failures overlie various crystalline and sedimentary bedrock types. In the largest area of concentrated slope failure, the loess is draped over Triassic granite. Other areas of extensive failure overlie Paleoproterozoic gneiss, Early Carboniferous diorite and granodiorite, and Miocene and Pliocene sandstone (or metasedimentary quartzite) and clastics.
Some of the loess flows are possibly dry-fluidized powder flows triggered by earthquakes, but some fraction of them also show the likelihood of variable water contents (Fig. 4), as well as possible subsequent modification by water so that they are difficult to differentiate from imagery alone. The reason that the majority of the mass movements in loess are located in this relatively small area is not clear, but could be related to the common seismicity, or perhaps to other factors.

At least some failure seems to be related to farming practices, which involves common channel irrigation (now discouraged in the China Loess Plateau in favor of the less destructive spray irrigation; Derbyshire et al., 2000), overgrazing, and heavy cultivation, which can cause the top layer of loess to retain water, which in turn adds load. Many of the valleys in Afghanistan with wide-spread slope failure have irrigation channels directly above the failed regions. Although this would have to be investigated in the field to confirm before any recommendations were made, water running through the irrigation channels or track ruts may be saturating and fluidizing the slopes (Fig. 4A and C).

Other possible explanations are fluvial and rain variations due to topography, as well as differences in loess thickness over underlying bedrock. Aspect direction of the mass movement on slopes could have a slight impact, as the south and west-facing slopes in the northern hemisphere get more sun, are warmer and drier, and have less vegetation cover (Bettis et al., 1986). Along with the primary slope failures are associated features in the loess topography such as karst-like topography and piping exits (Fig. 5).

Measurements of loess slope failures were obtained from the Google Earth™ imagery (Table 1). This software can produce fairly accurate measurements of failure-run length and width of the movement mass, but is less reliable for calculating depth (thickness). Calculated volumes can only be applied to very broad and general uses, as a minor difference in thickness can change the calculated volume significantly. Lengths were measured in the direction of movement, and ranged 78–733 m. Widths were measured perpendicular to movement direction and ranged 25–521 m. The mean length and width were, respectively ~260 m and ~150 m. Depth estimates of slide masses ranged ~1–16 m, and averaged ~3 m. Average calculated volume of
loess failure masses, where such data could be collected reasonably, was
~157,000 m³, or ~1.57 x 10⁻⁴ km³.

![Fig. 4. Loess slope failures; (A) loess flow beneath ridge-top road, possibly initiated by concentrated flow in tire ruts; (B) loess-slope failure near a dry river bed (bottom center), which was caused possibly by removal of toe or undercutting; (C) possible rapid wet debris flow, again initiated along a road; (D) loess slope failures in older failure mass; an older loess failure (with road cutting through) in farmland, with younger loess slope failures developing along the bottom of the slide mass.](image)

The majority of the failed slopes faced north, west, and north-west. This relationship is shown by the rose diagram of slope-aspect frequency of loess slope failures (Fig. 6). Out of 34 slopes, only a few had easterly slope aspects, and none faced south. It is suggested that the prevailing westerly winds leave west-facing slopes with increased soil moisture, making them more prone to saturation and collapse, especially during the long rainy season (October through April). Reduced evaporation on the cooler and damper northern slopes, and potentially higher freeze–thaw could also contribute. Also, the sun in the northern hemisphere is focused on south and west-facing slopes during the hottest part of the day, which then have a tendency to get more
sun, stay dryer, and have less vegetation.

Fig. 5. Features associated with loess; (A) arcuate crown cracking in loess. The loess in this area is heavily modified by slope failure and/or fluvial activity; (B) lake dammed by wet debris flow in loess (C) loess karst-like topography; (D) piping exits.

Another potential explanation is that, because relief increases to the east, there should be more slope area facing to the west, although this would have to be investigated further for confirmation. Were this actually the case, one could expect a slight increase of slope failures facing west, with all other things being equal. Additionally, due to the easterly topographic rise, west-facing slopes may be steeper. Because, however, prevailing westerly winds bring more storms from that direction, it appears that more slope failures can occur on west-facing slopes, and when combined with cooler, wetter northerly aspects, the combination results in a dominant northwest trend for the loess slope failures.
Table 1
Loess failures in northeastern Afghanistan. See Fig. 1 for general locations.

<table>
<thead>
<tr>
<th>Loess mass movement</th>
<th>Average length (m)</th>
<th>Average width (m)</th>
<th>Estimated thickness (m)</th>
<th>Approximate volume range (m$^3$)</th>
<th>Slope aspect</th>
</tr>
</thead>
<tbody>
<tr>
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<td>102</td>
<td>147</td>
<td>3-4</td>
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<tr>
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<tr>
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<td>130</td>
<td>87</td>
<td>3</td>
<td>33,780</td>
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</tr>
<tr>
<td>4</td>
<td>138</td>
<td>176</td>
<td>2-4</td>
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<tr>
<td>5</td>
<td>592</td>
<td>233</td>
<td>1</td>
<td>138,150</td>
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</tr>
<tr>
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<td>352</td>
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<td>No data</td>
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<td>7</td>
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<td>8</td>
<td>108</td>
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<tr>
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<tr>
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<td>7250–14,510</td>
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<tr>
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<td>112</td>
<td>1-3</td>
<td>21,170–63,510</td>
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Discussion and conclusion
Where wind-blown dust has blown up into mountain foothills in and across the underlying crystalline rocks northeastern Afghanistan, the loess has been deposited as blankets over pre-existing topography so that extensive small slope failures of loess can result. Field work should be conducted to determine the exact reasons for this, although it is suggested that the concentration is due to seismic area, topography, bedrock and other natural environmental and human practices (precipitation and loess thickness...
variations). Also of interest is the uniformity of slope aspect. Field work is currently
difficult in Afghanistan due to insurgency; remote satellite imagery remains the safest
and most reliable way to study the country for now.

Fig. 6. Rose diagram showing the slope-aspect frequency of loess slope failures.

Though the small volumes of the failure masses do not suggest any
immediate hazard to life, earth flows and slides pose risk to livestock and farmland.
Blocked or collapsed roads impede communication and supply routes. Care must
be taken by residents with farming and grazing practices, road design and location,
and building sites, and an awareness of the instability and other hazards should be
kept in mind during any development efforts.

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