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GROUND FAILURE PRODUCED BY THE 29 APRIL 1991 RACHA EARTHQUAKE IN SOVIET GEORGIA

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PREFACE

On 29 April 1991, a magnitude 7.2 earthquake struck the Racha region of the central Caucasus Mountains in Soviet Georgia. Approximately 100 people were killed by this earthquake; at least half of these fatalities occurred as a direct result of landslides triggered by the earthquake. The Institute for the Physics of the Earth of the Soviet Academy of Sciences requested that the U.S. Geological Survey send scientists to assist in the post-earthquake investigation in the epicentral region. As part of this team, we were sent to document and interpret primary and secondary ground failure caused by the earthquake. We worked with Soviet scientists in the epicentral region from 10-19 May. This brief report was written while in Soviet Georgia and was given to our Soviet colleagues at the time of our return to the United States. The report includes a summary of our field reconnaissance observations and some preliminary interpretations.

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INTRODUCTION

On 29 April 1991, a magnitude 7.2 earthquake struck the Racha region of Soviet Georgia. Normally, earthquakes of this magnitude trigger several types of ground failure including primary fault rupture and secondary (shaking-induced) ground failure including landslides and liquefaction. We conducted a reconnaissance survey in the epicentral region from 10-19 May to document earthquake-triggered ground failure.

We observed no tectonic surface rupture associated with this earthquake. Lack of surface faulting associated with an earthquake of such large magnitude, while atypical, is not unprecedented; the absence may be due to a deep hypocenter and (or) to rupture of a shallow-dipping blind thrust. However, our observations are limited to a small region, and surface rupture could have occurred that has not yet been found. Because surface rupture can occur on previously unmapped faults at some distance from the epicenter (for example the 1952 Tehachapi, California earthquake) or can form during aftershocks some time after the main event (for example, the 1985 Coalinga, California earthquake), surface faulting could be found with an ongoing, systematic search in a broad area surrounding the epicentral region.

We observed no evidence of liquefaction anywhere in the epicentral area. Landslides, however, are abundant. Five major types of landslides are prevalent (in decreasing order of relative abundance): rock falls, debris slides, earth slides, slumps, and rock block slides. Landslide type appears closely related to the lithology and geologic structure in the area. This report discusses each type of landslide and provides several specific examples from the epicentral region typical of these types.

ROCK FALLS

Rock falls are landslides in rock where the predominant movement is by falling, rolling, and (or) bouncing. Rock falls typically are among the most abundant landslides triggered by earthquakes, based on surveys of worldwide earthquake-induced landslides. Rock falls generally form on slopes steeper than 50° consisting of bedrock that is jointed, weathered, or otherwise deformed.

In the epicentral region, rock falls triggered by the earthquake are abundant from near-vertical escarpments in Mesozoic limestone and on local steep slopes in Jurassic volcanic rocks. Steep road cuts and stream cuts also produced many rock falls. A prominent limestone escarpment south of Bokva produced several large rock falls. The scarp is several tens of meters high and is nearly vertical. The escarpment is on the north flank of an anticline; thus, the limestone dips as steeply as 40° out of the escarpment. The limestone has random joints but is not pervasively fractured. The rock-fall deposit consists of blocks ranging in size from a few centimeters to perhaps 5 m across. The deposit abuts the base of the scarp and extends down the steep slopes below the scarp. The slope angle of the deposit in one location is 55°. The larger blocks, which measured a few meters across, had bounced after initial impact and left prominent craters in the ground; successive crater marks are a few meters apart and indicate high-speed movement.

The rock falls south of Bokva completely destroyed the road to Usholbta. The deposits remain extremely unstable and will present a continuing hazard, particularly during strong aftershocks or intense rainfall. Loose blocks remaining on the escarpment will probably continue to fall for some time until the rock mass fractured by the earthquake shaking is completely removed. The rock-fall deposit will likewise continue to slide downslope for some time.

DEBRIS SLIDES

Debris slides are landslides composed of earth and rock that move primarily by sliding along a planar or gently curved basal shear surface. Debris slides tend to disaggregate during movement and produce loose, heterogeneous deposits. Worldwide data indicate that debris slides are, with rock falls, the most abundant type of landslide triggered by earthquakes.

In the epicentral region, debris slides occur primarily on very steep to moderately steep slopes. Road cuts and cut banks along streams and rivers are common locations for debris slides. The slide material generally is colluvium and residuum derived from volcanic rocks and alluvium from stream terraces. Debris slides in the area range from a few meters across to several tens of meters across and hundreds of meters long.

EARTH SLIDES

Earth slides consist of fine-grained (diameter less than 2 mm) engineering soil that moves downslope along a planar or gently curved basal shear surface. Earth slides are relatively uncommon in worldwide earthquakes, but can occur in abundance where geologic conditions permit.

In the epicentral area, the earth slides occur almost exclusively in Oligocene and Miocene clays. The clays are bedded and show intense, complex deformation; they weather to form a weak, plastic soil that can absorb large amounts of water. Most areas containing extensive exposures of the clays appear to have experienced ancient and (or) recent landslide movement related to seasonal rainfall. Many locations that showed fresh-looking landslide cracks had moved recently during spring rains but before the earthquake. These active landslides generally experienced renewed movement during the earthquake, but, with few exceptions, they only moved a few centimeters to a few decimeters. Thus, distinguishing pre-earthquake landslide movement from earthquake-induced movement requires careful investigation of each site. We examined three earth-slide areas in detail.

A large earth-slide complex near Zhashkva covers about 2 km^2. Eyewitnesses stated that only a few small cracks formed during the earthquake and that the major movement began three days later and continued for two days. They stated that the movement did not appear related to rainfall or strong aftershocks. The entire area appears to be an ancient landslide complex. The upper margins of the slide are near a slope break high on the hillside, and the slide extends to the valley bottom. The upper margin is broadly arcuate but is locally irregular. Discrete lobes in the complex converge to a central axis defined by a preexisting drainage basin. Displacement across the headscarps of some lobes is only a few decimeters; other lobes have high head scarps and multiple internal scarps containing grabens and extension fractures with a total displacement of as much as 20 m. Many fractures have standing water only 1 or 2 decimeters from the ground surface. Many sag ponds were present before the earthquake, and many more formed as a result of the earthquake-induced movement. In the central part of the slide complex, two lobes collided and formed a prominent east-west-trending ridge. The ridge is bounded on one side by a steep scarp about 3 m high and on the other side by a zone of folding and thrusting. The landslide mass that moved during the earthquake contains several preexisting ridges and gullies, and the head scarp crosses this topography indiscriminately. This indicates that the basal shear surface is very deep, perhaps 30-60 m. The overall geometry of the slide mass suggests that the basal shear surface is planar; only near the head scarp is backward rotation evident, which indicates the shear surface becomes listric there and intersects the ground surface.

This earth slide is in an area of preexisting landslide movement, therefore continuing movement is likely. The earthquake-induced movement created many open fractures and closed depressions that will enhance ground-water recharge on the slide. Renewed movement is thus likely during or after periods of intense and (or) prolonged rainfall. Also, headscarps on landslides of this type commonly migrate upslope in the weeks and months following initial movement, so areas upslope from the existing slide may be endangered in the near future. Several houses in Zhashkva lie above new landslide cracks and could be damaged by enlargement of the existing slide.

The second earth slide we investigated totally destroyed the village of Chordi. The slide was a reactivation of an active earth slide in a valley underlain by Miocene clays. The slide averages about 500 m wide and 1,000 m long and appears to be 30-50 m deep; thus, the volume is 15,000,000-25,000,000 m^3. The main scarp shows 20-30 m of vertical displacement, and the upper part of the slide contains pervasive extension fractures. The weak clays were severely deformed and disaggregated along the main scarp and the slide margins, and drainage was diverted to flow along these margins, which has created mud flows that extend along most of the length of the main scarp and the lateral margins. The lower part of the slide has been thrust above the surrounding ground surface and the right margin is defined by a steep lateral scarp about 4 m high. The toe of the slide is convex and has been folded; the front part of the toe failed by toppling and forms a very steep, highly fractured and disrupted surface. Eyewitnesses state that the slide had been active in some areas before the earthquake, and that the earthquake caused only minor slide movement and structural damage to homes. About two or three days after the earthquake, the slide began to move at a rate of about 8 m/day; this rapid movement caused virtually all the structural damage and destroyed the village. At the time of our visit (18 May 1991), the slide was moving about 2 m/day; the main scarp, slide margins, and toe were actively sliding and enlarging at this time. The total movement of the slide since the earthquake is estimated to be 50-70 m, based on offset fences and roads.

The Chordi earth slide will, in all likelihood, continue to move for at least several weeks or months. The slide has been active in the past and will likely reactivate each year during or after periods of prolonged rainfall. Thus, rebuilding at this site probably will be impossible.

We investigated a third earth slide immediately east of Ambrolauri. From a distance, this slide appeared to have very fresh cracks and to have been triggered by the earthquake. Close inspection of the slide showed that almost all the visible displacement had occurred during this spring but definitely before the earthquake, as evidenced by vegetation growing in cracks. A few new open fractures were present that were triggered by the earthquake, but total displacement is only a few decimeters. Thus, identifying landslide movement as having been triggered by the earthquake requires careful examination of each site.

SLUMPS

Slumps are landslides that move along a concave-upward shear surface and thus rotate headward as they move; the landslide mass generally moves as an intact mass.
Slumps are common along roads throughout the epicentral area. Typically, slumps can be identified by arcuate cracks in a roadbed cut into a slope or in other sloping areas. Many roads in the area experience slumping in nonseismic conditions, so identifying earthquake-triggered slumps is sometimes difficult.

The town of Iri is built on the head of a large, ancient slump that has had recent activity. The slump consists of deeply weathered volcanic rocks of Jurassic age. During the earthquake, extensive cracks formed near the base of the scarp and high on the slope above town. The cracks in town had a few decimeters of total offset and extended through several structures; the cracks above town are reported to be too large to step across. The slopes below the town are precipitously steep, are subject to fluvial erosion, and contain several shallow slides and slumps. The cracks caused by the earthquake could be relatively shallow and not cause any further problem. However, it is possible that they extend to great depth and could lead to ongoing slide movement that could cause severe damage to most or all of the town. A small possibility of rapid catastrophic failure also exists.

ROCK BLOCK SLIDES

Rock block slides are landslides in rock that move along planar or gently curved basal shear surfaces; the landslide block remains essentially intact and moves as a coherent block. Rock block slides generally are much less abundant during earthquakes compared to rock falls and debris slides. Rock block slides commonly are controlled by local geologic structure, such as joint systems or bedding planes.

We studied two rock block slides in the epicentral region, near Usholbta and Shkmeri. The rock block slide near Usholbta is about 50 m wide and 30 m long. It lies on the south flank of an anticline composed of Cretaceous sedimentary rock that dips about 10° south. The local slope, formed by a stream, is oblique to the dip of the bedding. The slide block rotated outward from the slope about a vertical hinge line; thus, the right flank of the slide moved about 20 m, and the movement decreased to zero at the left flank of the slide. This created a V-shaped gap between the scarp and the slide block. The scarp is nearly vertical and ranges from 7 to 15 m high. The basal shear surface dips rather gently, as evidenced by concordant height of the scarp and top of the slide block. As the slide block moved outward, it compressed and deformed the slope in front of the toe. This slide displaced and blocked the road from Usholbta to Bokva.

The rock block slide near Shkmeri also lies on the south flank of the anticline; here, limestone dips 20-40° southward concordant with the local slope. Dark brown residual and colluvial soil 0.2 to 2 m thick mantles the limestone beds. The slide is about 625 m wide, 150 to 200 m long, and averages about 15 m thick. The volume is about 2,000,000 m^3. The main scarp extends parallel to the contours of the slope and undulates slightly. The right and left margins extend directly downslope along preexisting gullies. The main scarp is about 20 m high on the right flank and decreases in height to less than 1 m near the left flank. Displacement is also greatest on the right side of the slide; it ranges from 50 m there to a few meters on the left flank. The central part of the slide is a fairly intact block that contains several large fractures, some as deep as 10 m. The bottom one-third of the slide mass is a compressional zone containing folds with fractured crests and low-angle thrusts. Boulders dislodged from the slide mass rolled to the base of the slope. This slide destroyed a local road.

These two rock block slides will erode quickly during rainstorms in the next several years. Although some continuing movement may occur during wet periods or large aftershocks, this movement probably will be limited and should not pose a hazard to the nearby villages. The local geomorphology suggests that large landslides of this type have occurred anciently in this area.

DISCUSSION

The entire epicentral area contains many ancient and active landslides. Except for the rock block slides, all types of landslides that were triggered by the earthquake had preexisting analogues. The rock block slides, however, are not reactivated features.

Landslide types and locations are strongly controlled by lithology and geologic structure. Near-vertical limestone escarpments and volcanics exposed in steep road and stream cuts produce rock falls; steep slopes in alluvium, colluvium, and residuum produce debris slides; Oligocene and Miocene clays produce earth slides; dip slopes in competent bedrock produce rock block slides; and deeply weathered bedrock in some areas produces slumps.

The small amount of earthquake-triggered movement on many existing active earth slides is unexpected. Many of these slides had experienced movement during spring rains within weeks of the earthquake, and ground-water levels remain high as evidenced by standing water in open fractures. Thus, these earth slides probably have static factors of safety only slightly above 1.0. (Factor of safety is the ratio of resisting forces that tend to inhibit landslide movement to driving forces that tend to cause landslide movement; thus, slopes having a factor of safety greater than 1.0 are stable, and those with a factor of safety less than 1.0 should move.) Dynamic analysis indicates that slides having such low factors of safety should move large distances when subjected to strong shaking in an earthquake of this magnitude. At least two reasons for the small observed movement are possible. The duration and (or) intensity of the shaking produced by this earthquake may have been lower than normal for earthquakes of this magnitude. This possibility could be tested only by studying strong-motion records from the epicentral region. A second possibility is that the predominant frequency of the strong shaking was outside the range that would trigger movement of large landslides. High-frequency strong shaking typically produces smaller landslides in brittle materials; lower frequency shaking is required to trigger movement of larger landslides in more ductile materials.

The three-day delay between the earthquake and the major period of movement of the earth slides at Zhashkva and Chordi is difficult to explain. Apparently, the inertial effects of the earthquake shaking induced only minor movement of the slide masses, which was followed much later by the major movement. The small inertial movement at the time of the earthquake may have induced enough strain to reduce the soil shear strength below peak strength and possibly to increase pore pressures on the failure surface. In this reduced strength condition, the slides probably had factors of safety slightly below 1.0, which resulted in very gradual creep; the creep further reduced shear strength to residual level and increased pore pressures, and this further reduced the factors of safety and resulted in accelerated slide movement. This type of "creep-to-failure" phenomenon has been documented in landslides elsewhere.

In summary, this region has had ongoing landslide hazards even in the absence of earthquakes. The earthquake of 29 April 1991 reactivated many existing landslides and triggered many new landslides. These landslides pose an ongoing hazard to local inhabitants because some may experience continuing movement and some may actually enlarge and threaten nearby structures and roads.