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Prehistoric landslides: significance, recognition, examples

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Prehistoric landslides: significance, recognition, examples

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Abstract

Prehistoric landslides with a wide range of ages and sizes exist worldwide in both rock and soil. Many are thought to have occurred during Pleistocene time when climates in some areas were harsher and wetter. Subsequent weathering and erosion have subdued topography and other features of prehistoric landslides, often making them difficult to recognize. Recognition is the key to dealing with prehistoric and other old landslides. Old slide masses are usually only marginally stable because past movements reduced available shear strength on their failure surfaces to residual levels. These masses are susceptible to reactivation by construction activities, heavy precipitation, and earthquakes. If prehistoric landslides are recognized, they can be avoided or steps taken to minimize interference with them. Where they cannot be avoided, they must be stabilized or lived with. Stabilization typically involves robust retaining structures, large buttress fills, or excavation of most of the slide mass - all of which are expensive. Living with old landslides may involve continuing maintenance for distress caused by creep or other movements; this can also be expensive. Problems arise when prehistoric and other old landslides are unrecognized, then reactivated during or after construction. Then, unexpected ground movements cause damage, increase costs, set back construction schedules, and disrupt partially completed or completed facilities and operations. Geologic considerations, features of prehistoric and old landslides, and guidance for recognizing them are presented. Then examples of prehistoric landslides in the United States, Papua New Guinea, and Australia are given.

1 Introduction

Prehistoric landslides (sometimes called ancient landslides, colluvial landslides, or simply old landslides) are more common than generally appreciated. These landslides exist throughout the world in both rock and soil ranging in age from Devonian, and probably even older, to Holocene (Recent). Some prehistoric landslides occurred millions of years ago and others only a few centuries ago (Wikipedia 2022). Many are thought to have occurred during Pleistocene time (2.6 million to 11,700 years ago) under periglacial conditions when climates were harsher and wetter and erosion was more active (Peltier 1950, Hutchinson 1991, Hamel 1998). In eastern Australia, the preceding interglacial cycles are considered by some to have been progressively wetter than the current interglacial, and some of the “ancient landslides” and colluvial deposits may have developed during these earlier cycles. Seismic events may have triggered certain prehistoric landslides.

Some prehistoric landslides are huge and others are relatively small (Wikipedia 2022). Regardless of size, subsequent weathering and erosion is likely to have subdued landslide morphology, making recognition often difficult with remote sensing techniques and in the field.

Recognition of prehistoric landslides is the key to dealing with them. Recognition is important in connection with engineering works because these landslides are usually only marginally stable. If they are not recognized, remedial designs for other perceived causes may lead to expensive and ill-advised construction. Old landslides can be reactivated by construction activities, e.g., toe excavation, fill loading, and surface and subsurface drainage changes, as well as by heavy precipitation and earthquakes. The marginal stability of prehistoric and other old landslides results from past movements reducing available shear strength along failure surfaces to residual or near-residual levels (Skempton 1964, 1985). Creep and intermittent sliding of old slide masses over time tend to keep strengths at or near residual levels.

Peck (1967) noted:

> *The likelihood of reactivating old slide areas by apparently minor construction activities is not a new conception. Experts in air-photo interpretation and geomorphologists have been pointing out the implications of old slide areas for years. They have gone so far as to suggest that, if there are no old landslides in an area, it is fairly unlikely that a moderate construction operation will start a new one. On the other hand, if old landslides abound, it is quite likely even minor construction operations will lead to sliding.*

If prehistoric or other old landslides are recognized, steps can be taken to avoid them or minimize interference with them, e.g., by relocating facilities or by modifying alignments and grades of roads, railroads, and pipelines. If these landslides cannot be avoided, recognition will guide development of appropriate investigation and monitoring programs, cost estimates, construction schedules, and project funding. Recognition of these landslides may also modify or eliminate projects because of economic considerations.

Where prehistoric landslides cannot be avoided, they must be stabilized or lived with. Stabilization typically involves robust retaining structures, large buttress fills, or excavation of most of the slide mass, all of which are expensive. Alternatively, it is sometimes possible to live with prehistoric landslides, with continuing maintenance of facilities damaged by creep or intermittent sliding movements. This can also be expensive over time.

Problems arise when prehistoric and other old landslides are unrecognized, then reactivated during or after construction. These unexpected ground movements cause damage, increase costs, set back construction schedules, and disrupt partially completed or completed facilities and operations.

Examples of prehistoric landslides in the United States, Papua New Guinea, and Australia are given in this paper to illustrate the above concepts. Before these examples, however, some guidance on recognition of prehistoric landslides is presented.

2 Recognition of prehistoric landslides

2.1 Regional experience

Prehistoric landslides can exist almost anywhere, but they are most commonly found in topographic and geologic settings known for high overall landslide incidence. For example, the Landslide Overview Map of the Conterminous United States (Radbruch-Hall et al. 1982) shows several areas of High Landslide Incidence. The largest of these is the Appalachian Plateau of the eastern United States which is well known for prehistoric (and old) landslides (Gray et al. 1979, Hamel 1980, Lessing et al. 1976, Pomeroy & Davies 1975, Pomeroy 1982). It is prudent to assume that every soil-covered natural slope in the northern portion of the Appalachian Plateau has one or more old landslide masses unless proven otherwise (Hamel 2022a).

Another area of High Landslide Incidence shown on the above-mentioned Landslide Overview Map is the coastal portion of California, which is also well known for prehistoric landslides (e.g., Day & Thoeny 1998, Johnson & Cotton 2005).

Yet another well-known area of prehistoric landslides in the United States and Canada is the Cretaceous and Tertiary age clay shale region of the Northern Plains (Fleming et al. 1970). Brooker & Peck (1993) suggest that prehistoric landslides should be assumed to exist in valley walls of this region unless their absence can be conclusively demonstrated.

Within the Otway Ranges in southwestern Victoria and along the east coast within the Sydney Basin region of New South Wales (specifically the Illawarra, Blue Mountains and southern Hunter Valley), the Mullumbimby Region of northern NSW, also and within the Kuranda Range area of northern Queensland (along Stoney Creek), Australia, abundant large scale “ancient landslides” have been identified by numerous workers. Many larger scale topographic features (i.e., the Illawarra Escarpment which extends over 100 km of coastline south of Sydney to Nowra) are blanketed by colluvium. The Sydney Basin area of NSW is a Permo-Triassic Sedimentary Basin and comprises a sequence of coal seams, claystones (some thick and weak), siltstones and sandstones with some basaltic intrusives/extrusives.

Much of the regional development of prehistoric and other landslides results from the presence of thick, weak, slide-prone soil and rock units. In addition to the clay shales of the Northern Plains, these include thick, weak claystones, e.g., the Pittsburgh red beds of the Appalachian Plateau (Hamel & Flint 1972), the thick, weak mudstones of Papua New Guinea (Griffiths et al 2004), and the above-mentioned claystones of the Sydney Basin.

Regional experience with landslides in general, prehistoric landslides in particular, and thick, weak soil and rock units will guide investigations and assessments of prehistoric landslides. Engineering geologists and geotechnical engineers need training and experience in recognition of prehistoric landslides in each region in which they work.

2.2 Landslide maps

Prehistoric and other old landslides have been mapped in some areas where they are numerous, e.g., Southwestern Pennsylvania (Pomeroy & Davies 1975) and West Virginia (Lessing et al. 1976). Most of this mapping was done from aerial photographs with limited field checking. Some old landslides may have been missed due to sun angle and shadow on the aerial photographs. If there is no old landslide mapped at a particular site but a high density of landslides mapped in its vicinity, there is a high probability of an old landslide at the site.

2.3 Topographic and other surface features

Broadly speaking, the propensity for landsliding decreases with increasing maturity of the topographic landscape. Elevated areas, uplifted or extruded in the more recent geological past, tend to exhibit less mature landforms characterized by steeper slopes and higher rates of erosion. In particular, immature landforms are characterized by concave upper slopes leading to scarps at the crests of ridges and plateaus, and convex lower slopes adjacent to rivers and streams, where incisive erosion removes colluvium that continually accumulates in the base of the valley. By contrast, mature landscapes tend to exhibit convex upper slopes leading to rounded crests, and concave lower slopes with development of alluvial river flats adjacent to rivers and streams.

Procedures for recognizing landslides in general given by Rib & Liang (1978) are also applicable to prehistoric landslides. Topographic features useful for recognizing old landslide areas in the Appalachian Plateau are given by Hall (1974). Many of these features, including hillside swales and gullies, hillside bulges, run-out lobe structures, debris accumulation along slope toes, smaller active landslides, concave hillsides, hillside benches, and cirque-like amphitheaters near the tops of slopes, are relevant to recognition of prehistoric landslides elsewhere. These are well illustrated in Figure 1.

Amphitheaters and hillside benches are particularly characteristic. Many prehistoric landslides have an amphitheater below a vertical or near-vertical rock outcrop around the head scarp. Hillside benches, sometimes with closed depressions, ponded water, and near-by hummocky topography, are typical of prehistoric landslides in thick, weak rock units (Hamel & Flint 1972).

Other topographic features associated with prehistoric landslides are similar to those typical of recent, active landslides. In addition to the above-mentioned hummocky topography, these include tilted trees, power lines, and fence lines; structural distress, e.g., distortion, spalling, masonry cracks, sometimes patched and re-opened; pavement cracks and areas with multiple patches; scattered boulders with variable dips of beds or other lineations; ground cracks, scarps, and bulges; abnormal river or stream bends; anomalous bulges in valley sides and constrictions in valley bottoms; springs and wet areas; concentrations of animal burrows (in loosened slide material); and certain characteristic vegetation, e.g., cattails in wet areas and heavy concentrations of grape vines in certain Appalachian slide areas (Briggs et al. 1975).

The geomorphic features of prehistoric landslides are less easy to discern in more mature topographies and may not be apparent through surface mapping, particularly in heavily vegetated areas. Smaller scale features tend to be lost first, as erosion re-shapes the landslide-disturbed landforms, and in some cases local features such as cracks, bulges and slickensided surfaces can be erased relatively quickly. However, larger scale features may persist for thousands of years. Larger topographic features can often be seen more clearly on aerial photographs, including those of Google Earth. More recent remote sensing technologies such as LiDAR (Light Detection and Ranging) have proven particularly useful in this regard. Depending on the quality of the LiDAR and aerial photographs, these topographic features may be more obvious in the field.

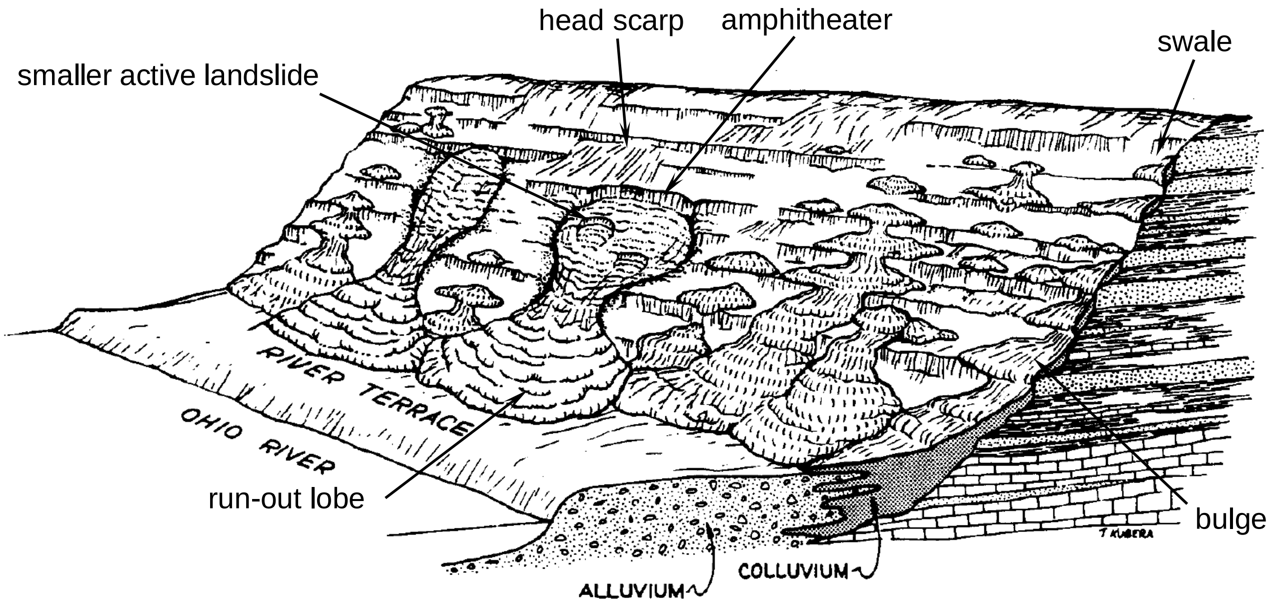


Figure 1. Schematic representation of the typical morphological features of prehistoric landslides (modified from Gray & Gardner 1977)

3 Examples of prehistoric landslides

3.1 Northern portion of Appalachian Plateau of Eastern United States

3.1.1 *General*

Prehistoric and other old landslides, along with colluvial slopes, were recognized here for many years (Wiggins 1909; Ladd 1927; Philbrick 1950, 1962), but it was not until the 1960s with the residual strength concepts of Skempton (1964) and progressive failure concepts of Bjerrum (1967) that real progress began to occur in understanding and dealing with them. The landmark project in this regard was the colluvial slope at a steel mill in Weirton, West Virginia (D'Appolonia et al. 1967).

3.1.2 *Steel Mill Slope - Weirton, West Virginia*

This slope is located on an abandoned meander channel 30 m above the Ohio River, about 100 km downriver from Pittsburgh, Pennsylvania. Colluvium (old landslide debris) interbedded with alluvium along the toe of this slope was to be excavated to a depth of 6 to 18 m over a length of 760 m for a steel plant expansion. The colluvium formed from flat-lying Pennsylvanian age sedimentary rocks and the alluvium was mainly Late Pleistocene age glacial outwash. The slope was thoroughly investigated ca. 1965-1966 according to concepts of Skempton (1964) and Bjerrum (1967). The toe excavation was successfully done after the slope was stabilized by a steel sheet pile wall anchored with tensioned earth ties. Radiocarbon dating of organic material excavated from colluvium indicated a minimum age of 40,000 years for the major movement of colluvium into the valley bottom (D'Appolonia et al. 1967).

Gray et al. (1979) describe another part of this Weirton steel mill slope where the toe was excavated in 1956 to develop a coal storage facility. This excavation caused slope movement. Among other remedial measures, a coal stockpile was placed as a toe buttress. Visual monitoring of slope movements governed the amount of coal removed from or added to the stockpile.

3.1.3 *Pike Island Lock Excavation - Wheeling, West Virginia*

The Pike Island Locks and Dam are 34 km down the Ohio River from Weirton, just north of Wheeling. In May 1960, when the project was under construction by the U.S. Army Engineer District, Pittsburgh, a massive landslide occurred on the landward (east) side of the lock excavation. The slide mass, which was approximately 1.2 km long, 82 m wide and 18 m deep, involved nearly 1.5 x 10^6 m^3 of colluvial and alluvial material. These materials were similar to those at Weirton. A tree branch from an old failure surface in the colluvium was found by radiocarbon dating to be approximately 9750 years old (Philbrick 1962, Gray et al. 1979).

This prehistoric slide was not recognized during investigation or design of the project which occurred before Skempton (1964) published his residual strength concepts. Remedial measures were designed by the Pittsburgh Engineer District on the basis of total strength shear strength parameters back-calculated from the slide. These measures included horizontal drains and a large buttress fill keyed into in-place rock (Gray et al. 1979).

3.1.4 *McMechen Slide – McMechen, West Virginia*

McMechen is a town 20 km down the Ohio River from Pike Island Locks and Dam. Portions of a prehistoric landslide approximately 1000 m long, 120 m wide and 13 m deep with a volume of approximately 1.5 x 10^6 m^3 and consisting of colluvial and alluvial soils (Figure 1) similar to those at Weirton and Pike Island were apparently re-activated by heavy precipitation in 1974 and 1975 (Gray & Gardner 1977). Stabilization included excavation of upper portions of the slide mass along with surface and subsurface drainage measures (Gray et al. 1980).

3.1.5 *Interstate Route 79 and 279 slopes – Pittsburgh, Pennsylvania*

Prehistoric landslides along a 2 km section of Interstate Route 79 (I-79) in a tributary valley of the Ohio River 15 km northwest of Pittsburgh were not recognized during investigation and design of the highway in the early to mid-1960s. Sidehill excavations for highway construction in 1968-1969 removed the toes of marginally stable landslide masses and initiated progressive failures which progressed upslope, in some locations to the ridgetop (Figure 2).

These prehistoric landslides were located high on the valley wall in flat-lying Pennsylvanian age sedimentary rocks similar to those at Weirton and Pike Island. Sliding occurred in a 20 m thick weak rock unit consisting primarily of the Pittsburgh red beds claystone. These slides brought down large blocks of the overlying 30 m thick, thick bedded to massive, Morgantown sandstone. Based on regional Pleistocene time correlations, the original rock slides probably occurred in Early Pleistocene (Illinoian or pre-Illinoian) time, on the order of 0.6 to 1.6 million years ago. Lateral stress release accompanying valley down-cutting (Ferguson & Hamel 1981), probably in conjunction with high pore and joint water pressures in valley wall rock due to periglacial precipitation (glacial ice front 30 km to northwest) and perhaps rapid drawdown of glacially ponded water, caused rock sliding along the valley wall (Hamel 1998). Subsequent sliding, creep, and weathering broke down the outer portion of the original rock slide masses into more typical colluvium. Long-term erosion subdued surface features of the slide masses but left well-defined topographic benches on them (Hamel & Flint 1972, Hamel & Adams 1981).

The slides were stabilized by excavating most of the slide masses to inclinations of 5H:1V to 3H:1V. This excavation caused additional movements and loosening of the Morgantown sandstone farther upslope in the most active slide area. This movement created a graben approximately 75 m long, 20 m wide, and 15 m deep at the ridge top. Slide debris downslope from the graben is still creeping at about 12 mm per year. This movement poses no threat to the highway because a 15 m wide catchment bench was excavated on the top of in-place rock below the basal failure surface of the old slide (Hamel 2022b).

Topographic benches and other features found during study of the I-79 slides were used to modify the design of a section of I-279 not then under construction in similar landslide terrain in another valley 4 km to the east. These modifications included changes in alignment and grade to avoid or minimize contact with prehistoric slide masses. No major slides occurrred there.

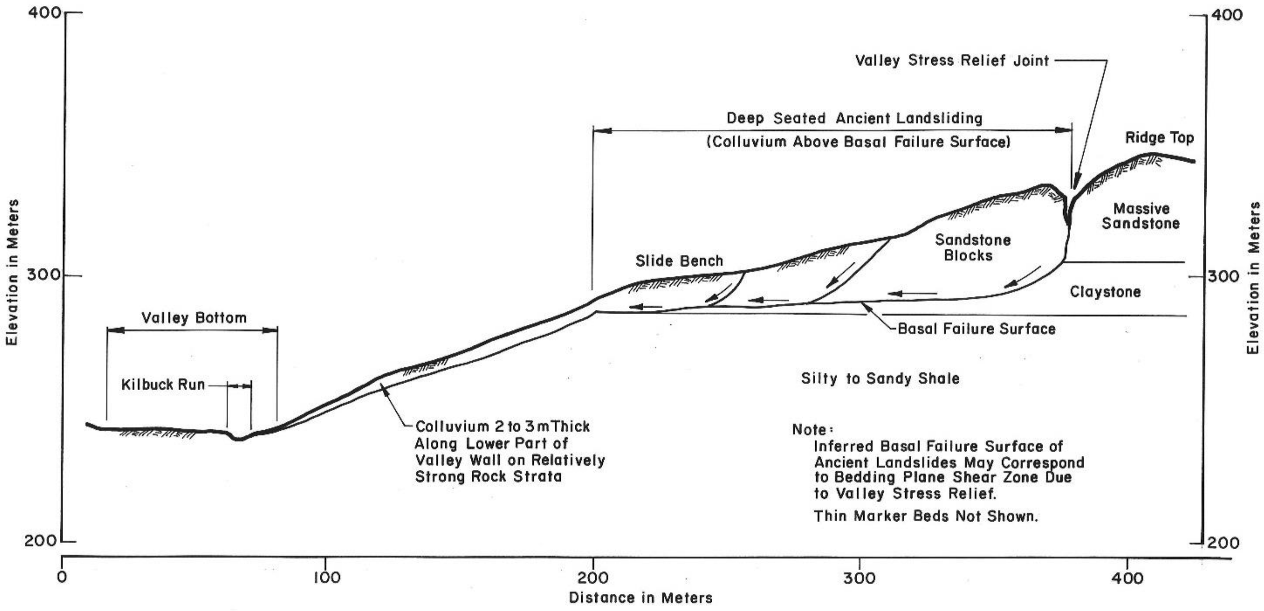


Figure 2. Cross-Section of Prehistoric Landslide at I-79 near Pittsburgh, Pennsylvania, after Hamel & Adams (1981) © 1981 Taylor & Francis Group, London, UK. Used with permission.

3.1.6 *Kilbuck Landslide – Kilbuck Township, Pennsylvania*

This site is located on the slope above the Ohio River 1.5 km southeast of the most active part of the I-79 slide area described above. Prehistoric landslides, rocks, and colluvium are similar to those at the I-79 site. A State Hospital operated here from 1862 to 1984 and had a long history of landslides. Aerial photographs taken in 1969 strongly suggest that this site was a partially eroded colluvial slide mass at or below the level of the Pittsburgh red beds.

A commercial development was planned for a 30 ha. portion of the site in 2002. The developer and his engineers failed to recognize or ignored the landslide history of the site and any colluvium that may have been encountered in the site investigation. As Glossop (1968) observed: "if you do not know what you should be looking for in a site investigation, you are not likely to find much of value."

The developer placed up to 30 m of fill on the unrecognized colluvium in the spring and summer of 2006. On September 19, 2006, the landslide occurred. It was 300 m long, extended 180 m upslope, and dumped 380,000 m^3 of material across a four lane highway and two of three railroad tracks along the Ohio River. Slide debris did not reach the third track or the river.

After the slide, heroic cleanup efforts re-opened the railroad and the highway and engineering investigations began for slide remediation. The slide area was eventually re-graded to what was considered to be a stable configuration, planted with vegetation, and surrounded by a security fence. Surface and subsurface instrumentation was used to monitor the slide during stabilization work. A May 12, 2014, newspaper article stated that remedial work was nearly finished with an estimated cost of $60 million (Hamel 2022b).

3.1.7 *Mt. Washington Slopes – Pittsburgh, Pennsylvania*

Slopes along the Ohio River across from downtown Pittsburgh were investigated in 1994-1995 for a proposed Airport Busway that was never constructed. These slopes, in the same flat-lying Pennsylvanian age sedimentary rocks as the I-79 site, have heights of 100-120 m and an average inclination of 1.5H:1V. Numerous prehistoric rockslides were found on these slopes along with typical colluvium. As at the I-79 site, these rock slides are thought to have occurred during Early Pleistocene time. Occasional rock falls and soil and rock slides from these slopes onto the railroad and road along the slope toe are removed as necessary. (Hamel 1998, Hamel et al. 1998).

3.1.8 *Yeager Airport reinforced soil slope – Charleston, West Virginia*

An unprecedented 73 m high Reinforced Soil Slope (RSS) was constructed in 2006 to extend a runway at Yeager Airport in Charleston, West Virginia, 270 km southwest of Pittsburgh. Tension cracks formed behind the slope crest in 2013 and the RSS failed catastrophically in 2015 (Berg et al. 2020, VandenBerge et al. 2021, Collin et al. 2021). Flat-lying Pennsylvanian age sedimentary rocks and related colluvium here are similar to those in the above-mentioned cases in the Upper Ohio River Valley and the Pittsburgh area.

The natural slope on which the RSS was constructed had several old (and probably prehistoric) landslides as well as recent landslides (Lessing et al. 1976). None of these landslides was observed or discovered in the woefully inadequate geotechnical investigation for the project. Portions of the old landslides, including basal failure surfaces, were left in place beneath the RSS fill. These old failure surfaces appear to have caused or contributed to progressive failure of the RSS (Hamel 2022a).

Extensive forensic investigations and litigation followed the failure (Berg et al. 2020, VandenBerge et al. 2021, Collin et al. 2021). Concurrently, remnants of the RSS and original slope were deconstructed and replaced by a 122 m long, 25 m high hybrid retaining wall system. Borings were drilled to obtain geotechnical information for design of this system (Cadden et. al. 2020).

3.2 Corps of Engineers Dams on Missouri River

From the 1930s to the 1960s, the U.S. Army Corps of Engineers designed and constructed several large multi-purpose dams on the Upper Missouri River. Most of this work was done in the early days of soil mechanics and well before the residual strength concepts of Skempton (1964). All of these dams and their reservoirs had slopes in thick, weak clay shale beds of Cretaceous to Tertiary age; most of these slopes had prehistoric landslides (Fleming et al 1970). Construction activities reactivated some of these slides, e.g., at Fort Peck Dam, Montana, and Oahe Dam, South Dakota. Most of these slides were remediated by excavating large quantities of slide debris, some of which was placed in stabilizing berms. Empirical studies of height vs. inclination of natural and excavated slopes in each clay shale formation, along with total stress stability analyses, were used to evaluate slopes and remedial measures (Fleming et al. 1970).

Prehistoric landslides in Bearpaw shale of the Fort Peck powerhouse slope were reactivated when their toes were excavated for construction of the reservoir outlet works and first powerhouse in 1934. Progressive failure and enlargement of the slide area continued until the early 1970’s when these slides were investigated using modern geotechnical concepts including those of Skempton (1964). Field residual shear strength parameters back-calculated from slides that occurred at various times were used to develop a grading plan to stabilize the slope. This plan involved approximately 1.24×10^6 m^3 of excavation and flattening the 60 m high slope to an inclination of 6H:1V. The slope appears to have remained stable since the excavation was completed in 1974 (Hamel & Spencer 1984).

3.3 Ok Ma Tailings Dam - Papua New Guinea

Foundation excavation for construction of a mine tailings dam removed toe support from unrecognized old landslide masses at a site in the rain forest highlands of Papua New Guinea. The initial slide reactivation on December 16, 1983, had an estimated volume of 3.4×10^6 m^3 and an area of 11 ha. The larger slide reactivation on January 6, 1984, had an estimated volume of 35×10^6 m^3 and an area of 122 ha. These landslides occurred in the Tertiary age Pnyang Formation mudstone and clayey siltstone, a weak rock unit ca. 1000 m thick, and in colluvium derived from this rock. The dam site was abandoned and extensive forensic investigations were done for subsequent litigation (Griffiths et al. 2004).

3.4 Eastern Australia

3.4.1 *General*

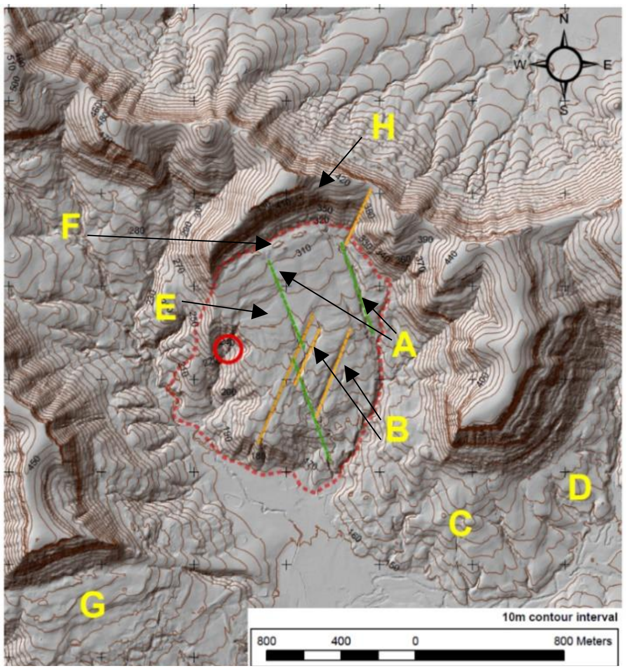
Although Australia is a tectonically-stable continent with many areas of mature, ancient landforms, the landforms along its densely-populated eastern margin include the Great Escarpment and Great Dividing Range (Ollier 1982). These host widespread examples of slope instability in diverse settings including Paleozoic fold belts, Permo-Triassic sedimentary basins, and Tertiary basalts (Branagan & Packham 1967).

3.4.2 *Jesmond, Newcastle, New South Wales (NSW)*

In this area of Permian coal measures, the Waratah sandstone, a 10-20 m thick marker bed of medium strength, lithic sandstone, separates the overlying Newcastle coal measures from the underlying laminated mudstones of the Tomago coal measures. The topography is mature and mild, with no evidence or history of slope instability in the area. In two locations, however, pockets of deep sandstone and mudstone colluvium indicate prehistoric mass movement in areas where it would not have otherwise been suspected. In one location, colluvium was exposed in the end of a 40 m deep highway cut without consequence; in the other, poor surface water management, uncontrolled fill placement and an excavation for a communications tower caused activation of a small slide that exposed the colluvium at the base.

3.4.3 *Congewoi Valley, Watagan Mountains, Hunter Valley, NSW*

A series of massive translational rock slides, up to 1 km wide, 1 km long, and many tens of m thick, have occurred where resistant thickly bedded Triassic sandstones overlie weaker Permian marine and coal measures sedimentary rocks. One of these slides has been walked over several times by the last two authors of this paper and has an estimated volume of 25 million m^3. As the Triassic strata tend to form plateaus with cliffs on their upper slopes, valleys are littered with rockfall debris, but otherwise the setting was historically considered to comprise typical valley-widening processes by stream downcutting and simple cliffline regression. However, when LiDAR data (with corrections for vegetation cover) became available, large scale morphological features could be clearly discerned that indicated valley formation through large scale, deep-seated mass movement as shown in Figure 3 (Fityus et al. 2019). The identified features, not readily discerned from field mapping, included extensive run-out lobes and benches, swales and unlikely arrangements of drainage features.



A, B	Lineaments associated with unusual drainage patterns
C, D	lobate structures fanning out from the base of steeper slopes
E	planar fan forming the main body of the slide
F	hummocks and swales at the toe of the backscarp
G	another slide runout zone at the toe of a steep backscarp, with lineaments parallel to the scarp
H	backscarp in bedded rock

(modified from Fityus et al. 2019)

Figure 3. LiDAR view of northern ridge of Congewoi valley showing a variety of landslide features.

3.4.4 *Mullumbimby Region, Northern NSW*

Upon first viewing, the landslide appeared to be a small one caused by heavy rain along a road on the upper side of a stream valley. Field viewing was restricted due to right of way constraints. However, upon viewing in Google Earth, it was apparent that the slide was in the toe of a massive prehistoric landslide, which occurred when the side of a ridge slid (Figure 4). The prehistoric slide rerouted a stream and left a large, relatively flat zone of slide material with areas of ponded surface and ground water and boulders at the base of the hillside. Additionally, several slides were visible in other areas of the sloping toe area of the prehistoric slide mass.

The site is within the Tweed and Focal Point Central Volcanic region which form overlapping shield volcanos, each approximately 100 km across. The rock at the site is within the area dominated by the Lismore Basalt of the early Miocene age Lamington Volcanics.

Borings encountered up to 19.3 m of an upper colluvial layer consisting of clayey to silty soil with a trace to some sand and gravel sized rock fragments, overlying a 3.9 m to 10.5 m thick lower colluvial layer consisting of boulders, rock fragments, and soil. A total of 23.2 m of colluvium was encountered in a boring at the toe of the slide mass. In some boings, the colluvium was underlain by silty and clayey residual soil underlain by basalt, which had altered and breccia zones.

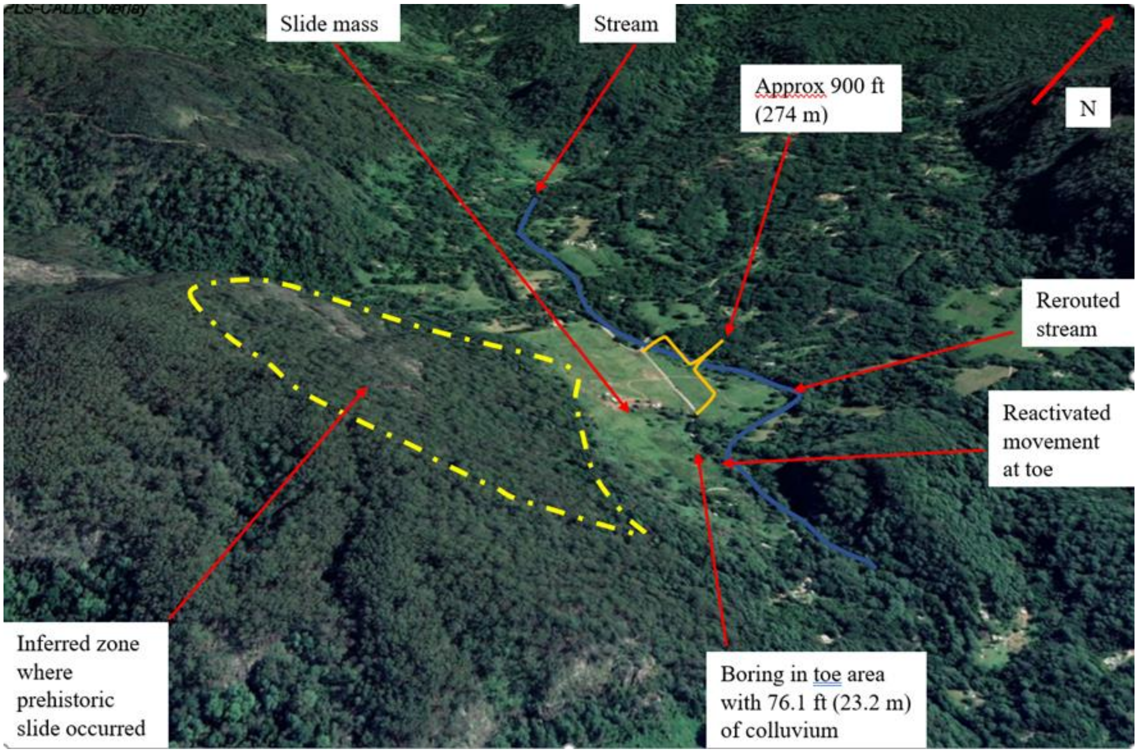


Figure 4. Overall view of Mullumbimby slide area.

3.4.5 *The Illawarra Escarpment, NSW*

The Illawarra Escarpment in New South Wales extends 100 km south of Sydney and beyond Wollongong to Nowra and it is quite similar to the schematic shown in Figure 1, although it has an upper cliffline of sandstone. The slopes of the escarpment are entirely blanketed by colluvium deposits and a landslide inventory developed by the third author of this paper over the last 25 years contains almost 2000 landslides within the Sydney Basin region. Over half of these landslides are situated along the Illawarra Escarpment yet these only represents about 3 or 4% of the escarpment area. The landslides comprise rock falls, debris flows and debris slides while the majority are slide type features with an average volume of approximately 30,000 m^3. The largest landslide is that in Congewoi mentioned above and several slides within the escarpment do approach the one million m^3 volume (Flentje et al. 2012, Fityus et al. 2019).

Numerous very large-scale embayment type ancient slide features have been identified on the escarpment and more than a few of these have smaller scale landslides within and around the margins.

In one large ancient translational slide near Stanwell Park in NSW, Australia, a road cut exposes a back-tilted rotational block of bedrock, with dips of near 45 degrees into the slope, within an otherwise near horizontally bedded sequence. Furthermore, this sequence of thickly bedded sandstone and siltstone bedrock, is approximately 30 m lower than where it belongs, situated within an underlying marker bed of very low strength chocolate colored claystone. This slide has a cross section very similar to the I-79 landslide shown in Figure 2 above. This landslide failed quite dramatically in 1889, taking out several hundred metres of then new railway and road. Repairs in the form of subsoil drainage tunnels were manually excavated and the work documented in a technical paper (Shellshear 1890). Movement of this site has not been recorded until March 2022. A centrally located cored borehole with inclinometer was drilled in 2015 and inclinometer monitoring has not shown any movement until prolonged and occasionally heavy rainfall throughout March 2022 (7 day totals of 360 mm and 90 day totals of 1600 mm) during which the inclinometer has shown 40 mm of movement at 14 m depth.

4 Conclusions

Prehistoric and other old landslides occur worldwide, are often difficult to recognize, and even when recognized, they sometimes cause major problems with substantial economic and environmental costs. These costs are usually much higher when prehistoric landslides are not recognized prior to construction activities and then reactivated by these activities.

5 References

Berg, R. R., Collin, J.G., Taylor, T.P., Watts, C.F. (2020). Case history on failure of a 67 m tall reinforced soil slope. *Geotextiles and Geomembranes*. 48: 802-811. https://doi.org/10.1016/geotexmem.2020.06.003.

Branagan, D.F., Packham, G.H. (1967). *Field Geology of New South Wales*. Science Press, Sydney, 191 pp.

Briggs, R.P., Pomeroy, J.S., Davies, W.E. (1975). Landsliding in Allegheny County, Pennsylvania. *U.S. Geological Survey Circular 728*, Washington, DC: USGS, 18 pp.

Brooker, E.W., Peck, R.B. (1993). Rational design treatment of slides in overconsolidated clays and clay shales. *Canadian Geotechnical Journal* 30: 526-544.

Cadden, A., Shull, P., Brill, G., Senior, M. (2020). West Virginia's airport in the clouds. *Geostrata*: 24 (3): 32-39.

Collin, J. G., Stark, T. D., Lucarelli, A., Taylor, T.P., Berg, R.R. 2021. Stability and stress- deformation analysis of reinforced slope failure at Yeager Airport. *Journal Geotechnical Geoenvironmental Engineering* American Society of Civil Engineers, Reston, VA 147 (3): 11 pp. https://doi:10.1061/ (ASCE) GT.1943-5606.0002454.

D'Appolonia, E., Alperstein, R., D'Appolonia, D.J. (1967). Behavior of a colluvial slope. *Journal of Soil Mechanics and Foundations* Division, American Society of Civil Engineers, New York, NY, 93: 447-473.

Day, R. W., Thoeny, S. (1998). Reactivation of a portion of an ancient landslide. *Environmental & Engineering Geoscience*, 4: 261-269.

Ferguson, H. F., Hamel J. V. (1981). Valley stress relief in flat-lying sedimentary rocks. In Akai, et al. (eds.), *Weak Rock.* Balkema, Rotterdam, the Netherlands, 2: 1235-1240.

Fityus S.G., Flentje P., Rigby R. (2019). Massive landsliding in Narrabeen sandstones in the Watagan region. *Proc 13th Australia New Zealand Conference on Geomechanics*, In Acosta-Martinez & Lehane (eds.) Perth, Western Australia. 493-498.

Flentje, P., Stirling, D., and Palamakumbure, D. (2012). An Inventory of Landslides within the Sydney Basin to aid the development of a refined Susceptibility Zoning. *Ground Engineering in a Changing World.* Proc. 11th Australia New Zealand Conference on Geomechanics. Australian Geomechanics Society. Melbourne.

Fleming, R.W., Spencer, G.S., Banks, D.C. (1970). *Empirical Study of Behavior of Clay Shale Slopes*, U.S .Army Engineer Nuclear Cratering Group, Livermore, CA, 2 Vol.

Glossop, R. (1968). The rise of geotechnology and its influence on engineering practice. *Geotechnique* 18: 105-150.

Gray, R.E., Ferguson, H.F., Hamel, J.V. (1979). Slope stability in the Appalachian Plateau, Pennsylvania and West Virginia, U.S.A. In Voight (ed.) *Rockslides and Avalanches, Vol. 2*. Elsevier, Amsterdam, pp. 447-471.

Gray, R.E., Gardner, G.D. (1977). Processes of colluvial slope development at McMechen, West Virginia. *Bulletin International Association of Engineering Geology*, No. 16: 29-32.

Gray, R.E., Gardner, G.D., Wimberly, P. M. (1980). Stabilization of a colluvial landslide in an urban area. *Proceedings International Symposium on Landslides,* New Delhi, India, 4 p.

Griffiths, J.S., Hutchinson, J.N., Brunsden, D., Petley, D.J., Fookes, P.G. (2004). The reactivation of a landslide during the construction of the Ok Ma tailings dam, Papua New Guinea. *Quarterly Journal of Engineering Geology and Hydrogeology* 37: 173-186.

Hall, G.A. (1974). The Development of Design Criteria for Soil Slopes on West Virginia Highways. Ph.D. Dissertation, West Virginia University, Morgantown, WV.

Hamel, J.V. (1980). Geology and slope stability in western Pennsylvania. *Bulletin Association of Engineering Geologists* 17: 1-26.

Hamel, J. V. (1998). Mechanism of Pleistocene rock slides near Pittsburgh, Pennsylvania. *International Journal Rock Mechanics Mining Sciences.* 35: Paper No. 32.

Hamel, J.V. (2022a). *Discussion* of Case History: Failure of the Reinforced Soil Slope at Yeager Airport, Charleston, West Virginia by VandenBerge, D.R., Valentine, R.J., Brandon, T.L., and Wright, S.G. *Journal Geotechnical Geoenvironmental Engineering*, American Society of Civil Engineers, Reston, VA, 148. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002430.

Hamel, J.V. (2022b). Interstate Route 79 and Toms Run Nature Reserve landslide areas north of the Ohio River and northwest of Pittsburgh. *Guidebook for Pittsburgh Geological Society 75th Anniversary Field Trip*. 85 pp. Available on PGS website at: https://pittsburghgeological society.org/pgs-field-guides.html

Hamel, J.V., Adams, W.R., Jr. (1981). Claystone slides, Interstate Route 79, Pittsburgh, Pennsylvania, USA. In Akai, et al. (eds.), *Weak Rock*, Balkema, Rotterdam, the Netherlands, 1: 549-553.

Hamel, J.V., Flint, N.K. (1972). Failure of colluvial slope. *Journal of Soil Mechanics and Foundations Division*, American Society of Civil Engineers, New York, NY, 98: 167-180.

Hamel, J.V., Lasko, J.D., Ruppen, C.A. (1998). Rock slope evaluation for Pittsburgh airport busway. In Moore & Hungr (eds.), *Engineering Geology – a Global View from the Pacific Rim*, Balkema, Rotterdam, the Netherlands, 5: 3421-3428.

Hamel, J.V., Spencer, G.S. (1984). Powerhouse slope behavior, Fort Peck Dam, Montana. In Prakash (ed.), *Proc. International Conference on Case Histories in Geotechnical Engineering,* St. Louis, MO, 2: 541-551.

Hutchinson, J.N. (1991). Periglacial and slope processes. In: Forster, A., Culshaw, M.G., Cripps, J.C., Little, J.A., Moon, C.F. (eds.), *Quaternary Engineering Geology*, Geol. Soc. Eng. Geol. Spec. Pub. No. 7, 283-331.

Johnson, P.L., Cotton, W.R. (2005). The Santiago landslide and associated ridge-top graben (sackhungen): implications for paleoseismic landslide studies. *Environmental & Engineering Geoscience* 11: 5-15.

Ladd, G.E. (1927). Landslides and their relation to highways, Part 1. *Public Roads* 8: 21-35.

Lessing, P., Kulander B., Wilson B., Dean S., Woodring S. (1976). West Virginia Landslides and Slide-Prone Areas. *Environmental Geology Bull. #15*. Morgantown, WV: WV Geological and Economic Survey.

Oilier, C.D. (1982). The Great Escarpment of eastern Australia: tectonic and geomorphic significance. *Australian Journal of Earth Sciences* 29: 13–23.

Peck, R. B. (1967). Stability of natural slopes. *Journal of Soil Mechanics and Foundations* Division, American Society of Civil Engineers, New York, NY, 93: 403-417.

Peltier, L.C. (1950). The geographic cycle in periglacial regions as it is related to climatic geomorphology. *Annals, Association of American Geographers*, 40: 214-236. Philbrick, S.S. (1950). Foundation, slope and embankment problems, Conemaugh Railroad relocation. In *Proceedings, Conference on Foundations and Embankment Construction*, Kansas City, MO, 1949, U.S. Army Engineers, Waterways Experiment Station, Vicksburg, MS, pp. 100-116.

Philbrick, S.S. (1950). Foundation, slope and embankment problems, Conemaugh Railroad relocation. In *Proceedings, Conference on Foundations and Embankment Construction*, Kansas City, MO, 1949, U.S. Army Engineers, Waterways Experiment Station, Vicksburg, MS, pp. 100-116.

Philbrick, S.S. *(1962). Old landslides in the Upper Ohio Valley. in Abstracts of papers submitted for six meetings with which the Society was associated: Geological Society of America Special Paper 68, Abstracts of Papers Submitted for the Meeting in Cincinnati November 2–4, 1961. p. 245-246*, https://doi.org/10.1130/SPE68-p125

Pomeroy, J.S. (1982). Landslides in the Greater Pittsburgh Region, Pennsylvania. *U.S. Geological Survey Professional Paper 1229*, Washington, DC: USGS, 48 pp + 12 plates.

Pomeroy, J.S., Davies, W.E. (1975). Map of Susceptibility to Landsliding in Allegheny County, Pennsylvania. *U.S. Geological Survey Miscellaneous Field Studies Map* MF 685 B, Washington, DC: USGS.

Philbrick, S.S. (1950). Foundation, slope and embankment problems, Conemaugh Railroad relocation. In *Proceedings, Conference on Foundations and Embankment Construction*, Kansas City, MO, 1949, U.S. Army Engineers, Waterways Experiment Station, Vicksburg, MS, pp. 100-116.

Radbruch-Hall, D. H., Colton, R.B., Davies, W.E., Lucchitta, I., Skipp, B.A., Varnes D.J. (1982). Landslide Overview Map of the Conterminous United States. *U. S. Geological Survey Professional Paper 1183*, Washington, DC: USGS, 25 pp + map.

Rib, H.T., Liang, T. (1978). Recognition and identification. In Schuster & Krizek (eds.), *Landslides Analysis and Control, Special Report 176*, National Academy of Sciences, Washington, DC, pp. 34-80.

Shellshear, W., (1890). On the treatment of slips on the Illawarra railway at Stanwell Park. *Journal of the Proceedings of the Royal Society NSW*. 24: 58 - 62.

Skempton, A.W. (1964). Long term stability of clay slopes. *Geotechnique* 14: 77-101.

Skempton, A.W. (1985). Residual strength of clays in landslides, folded strata, and the laboratory. *Geotechnique*, 35: 3-18.

VandenBerge, D.R., Valentine, R.J., Brandon, T.L., Wright, S.G. (2021). Case history: Failure of the reinforced soil slope at Yeager Airport, Charleston, West Virginia. *Journal Geotechnical and Geoenvironmental Engineering.* American Society of Civil Engineers, Reston, VA. 147: 12 pp. https://doi: 10.1061/(ASCE)GT.1943-5606.0002430

Wiggins, W.D. (1909). Slides and washouts. *Proceedings, Tenth Annual Convention, American Railway Engineering and Maintenance of Way Association*, Chicago, IL, Vol. 10, Part II, Appendix C, p.1089.

Wikipedia. (2022). Prehistoric Landslides. Accessed May 25, 2022.