Late Quaternary landscape evolution and genesis of the 2009 catastrophic landslide in the Hsiao-lin area, southwestern Taiwan

Meng-Long Hsieh a,⁎, Larry Syu-Heng Lai b, Chris Ding-Jyun Lin b, J. Bruce H. Shyu b

a Department of Earth and Environmental Sciences, National Chung Cheng University, Chaiyi, Taiwan R.O.C.
b Department of Geoscience, National Taiwan University, Taipei, Taiwan R.O.C.

Abstract

With cumulative rainfall of 1700 mm, Typhoon Morakot triggered a catastrophic landslide at Hsiao-lin (9 August, 2009), which dammed the river, buried the village and killed >400 people. We conducted a geomorphic study to understand the origin of this landslide in the context of the long-term evolution of the hillslope. The landslide originated from a broad, poorly drained slope (21°–23°) and ran down along two first-order channels. The erosion, up to 80 m thick, has created a concave-shape slope and exposed mostly loose debris, which implies that the landslide was mainly the reworking of ancient colluviums. The genesis of the concave-shape slope where the source sediments of the landslide resided reflects the weakness of the mudstone/shale bedrock underlying this slope, in contrast to the sandstone-based transport area. The two channels in the transport area also follow old faults or joints. Given that the source area has been subject to erosion during large landslides, the subsequent deposition here was likely achieved by minor colluvial processes. This deposition continued until the catastrophic failure in 2009, which could be controlled by (1) the amount of sediments deposited, which determined the slope angle, and (2) the headward expansion of the channels from the transport area, which enhanced groundwater convergence and later provided routes for the landslide materials to run downslope. Extensive mass-wasting motions had occurred in the area, as shown by the prevalence of >20 m thick landslide/debris-flow sequences on the lower part of the hillslope, which are dated 21, 14.9, 13.7 and 12.0 ka by the radiocarbon method. These mass-wasting events had hindered the long-term incision of the trunk river in response to the rapid tectonic uplift. At least the 12.0 ka event, which caused extensive mud-flow deposition, had dammed the river. Overall, this study shows how bedrock lithology and structures controlled the shape of a hillslope and caused extremely unsteady mass-wasting transport in the active mountains of Taiwan.

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1. Introduction

With frequent earthquakes and heavy rains, the rugged mountain area of Taiwan is prone to landslides and debris flows that have caused numerous losses in life and property. One of the most disastrous landslide events, killing >400 people, occurred on 9 August, 2009 at Hsiao-lin Village along the Chi-shan River in southwestern Taiwan (Fig. 1). This landslide, named Hsiao-lin, was triggered by extremely heavy rains brought by Typhoon Morakot (7–10 August). According to the rainfall recorded 11 km south of the village, the landslide occurred one day after the peak hourly rainfall, when the cumulative rainfall reached 1700 mm. The landslide, with a volume of $2.7 \times 10^7$ m$^3$ (Wu et al., 2011), buried the village and dammed the Chi-shan River. The subsequent dam-breaching caused wave surges that damaged the village further (Lee et al., 2009; Kuo et al., 2011; Tsou et al., 2011).

The catastrophic Hsiao-lin landslide has drawn many attentions. Most studies focused on the role of bedrock masses on the genesis of the landslide and regarded it as a dip-slope landslide, moving along the bedding planes of the underlying bedrock (Tsou et al., 2011; Wu et al., 2011), or a wedge-shaped landslide, controlled jointly by bedding planes, faults and joints of the bedrock (Lee et al., 2009; Tsou et al., 2011). A prominent controversy, however, has existed on the landslide sources (and therefore on the history of the hillslope before the landslide). Tsou et al. (2011) considered the landslide as a rockslide-rock avalanche, and proposed it to be preceded by gravitational deformation of the fractured bedrock. On the other hand, although not providing detailed data, many researchers recognized that the landslide originated from thick ancient colluviums pre-stored in the source area (Lee et al., 2009; Kuo et al., 2011; Wu et al., 2011). This statement implies that before the great erosion brought by the landslide, the area had been dominated by deposition.

We also observed abundant loose mass-wasting complexes, or colluviums, in the Hsiao-lin landslide area. In fact, these colluviums are the major materials exhibited on both the landslide surface and
the outcrops along the scarps/flanks of the landslide, even though up to 80 m thick materials were removed during the landslide as measured by Tsou et al. (2011) and Wu et al. (2011). Bedrock exposures, including those affected by gravitational deformation as shown by Tsou et al. (2011), are limited. These observations not only support the old colluviums as the major source of the landslide, but even question the significance of bedrock masses in the genesis of the landslide (i.e. most of the landslide may not move along bedrock surfaces).

Catastrophic landslides have rarely been reported as originating from old colluviums. Neither has such a phenomenon been underscored in the active mountains of Taiwan, where fluvial/mass-wasting agents have been considered efficient to flush out sediment (Hovius et al., 2000; Lin et al., 2009). It is important to understand whether the Hsiao-lin case is unique, conditioned by some unusual factors, or suggests an erosion/deposition process that has constantly been overlooked.

This study aims at the origin of the Hsiao-lin landslide in the context of the long-term evolution of the landscape. We have reviewed the geological/geomorphic settings of the Hsiao-lin area, examined the morphology and deposits of the landslide, and found some features that have not been mentioned by the former studies. We also have described the ancient colluvial sediments around the landslide, investigated the river terraces along the Chi-shan and its major tributaries, and obtained 12 radiocarbon dates for chronological constraints. Based on these data, we evaluate the role of bedrock masses on the Hsiao-lin landslide, reconstruct the area’s fluvial/hillslope histories, and elucidate the geomorphic controls on the genesis of the landslide.

2. Methods

This study followed the routine stratigraphy-based geomorphic approaches. The landscape features were first analyzed from the 1-to-25,000 scale, 10 m contour topographic map (before the Hsiao-lin landslide) and from the 5-m mesh DEM (after the landslide), provided by the Ministry of the Interior. The constituents of the landscape, including bedrock and sediments, were then examined in the field, and their heights and/or thicknesses (defined as the vertical distance between the highest and lowest parts of the sediments) were surveyed by laser rangefinder or estimated from the map or the DEM data. The color, grain size, roundness, texture and structure of the sediments were qualitatively observed, and their depositional environments were interpreted.

We also sought for fossil plants for radiocarbon dating, from not only old strata exposed on outcrops but also modern deposits on the surfaces of the Hsiao-lin landslide. Fossil plants found from the latter places are carbonized and compacted, readily differentiated from modern plant fragments, and must have been reworked from the strata upslope of where they were found, given that dead plants exposed to surfaces in humid tropical settings like Taiwan would quickly decompose (Hsieh and Chyi, 2010). The obtained radiocarbon
3. Geological and geomorphic settings

The gravely Chi-shan (or Nan-tzu-hsien) River, running between the Yu-shan Range in the east and a branch of the Ali-shan Range in the west, is one of the major south-flowing rivers draining the southwestern part of the Taiwan orogen (Fig. 1). Hsiao-lin Village is located on the midstream of the Chi-shan River (~40 km from the Ping-tung Plain; Fig. 1), along the margin of the modern floodplain north of the confluence with the Geo-pu River, a major tributary of the Chi-shan (Fig. 2). In this area, the peak heights of the Yu-shan and Ali-shan ranges relative to the main valley bottom are 1200 and 600 m, respectively. The Hsiao-lin landslide took place on a hillslope fringing a side ridge of the Yu-shan Range (Fig. 2). This hillslope is bounded, and somewhat isolated, by the Geo-pu River and another tributary (unnamed) of the Chi-shan River to the north (Fig. 2). Both rivers are deeply incised and underwent large-scale debris flows during Typhoon Morakot.

The topmost parts of the Ali-shan and Yu-shan ranges consist of gently rolling surfaces (Fig. 2). Except for those, the Ali-shan Range and the upper part of the Yu-shan Range, where the Hsiao-lin landslide originated, are characterized by relatively steep slopes (generally 25–30°), in contrast to the gentle, lower part of the Yu-shan Range. Many of the rivers draining the Yu-shan Range develop from the middle slope of the range (e.g., an unnamed river tributary near Hsiao-lin Village, labeled A) (Fig. 2). As a result, the lower slope of the Yu-shan Range, which comprises many small hills on interfluves (e.g., Hills 578, 590, and 560 around Tributary A), shows a greater degree of dissection than the upper slope of the range. The transition between the gentler, more dissected lower slope and the steeper, more intact upper slope commonly exhibits hummocky surfaces with disconnected drainages (Fig. 2; cf. Tsou et al., 2011).

The Chi-shan catchment is underlain by deformed Neogene sedimentary rocks (Fig. 1). The major structure in the catchment is the
Tsou et al. (2011) and Wu et al. (2011), the maximum deposition was much gentler than those exhibited in the source area. According to the terraces adjacent to Hsiao-lin Village, and dammed the Chi-shan bottom). This deposition occurred along the buried Tributary A (80 m thick) and downslope of the vanished Hill 590 (40 m thick) (Fig. 3b). Except for these two places, the deposition was generally ~20 m thick. Upslope of this deposition zone, a prominent depression was created and has been filled by an alluvial fan emanating from the “water slide” (Fig. 3b). This alluvial fan, constituted by sediments much finer than the surrounding landslide deposits, is believed to be formed after the event.

4.2. Deposits

Loose debris dominates over the entire landslide area (Fig. 3b). Tsou et al. (2011) have described this landslide deposit as consisting of individual boulders (blocks) of sandstone, shale/mudstone, and clayey, brecciated mudstone pebbles/cobbles. The latter are gray or dark-gray in color, and are generally matrix-supported. Tsou et al. (2011) also have pointed out the dominance of sandstone boulders around Ridge S. Except for this, no distinct changes of composition and texture of the landslide sediments have been found, from the source to the deposition areas.

Where the landslide deposits have been incised, along the gullies in the source area and by the Chi-shan River, they are shown as composed mainly of grayish clayey gravels, with the bouldery deposits only capping on the tops of the sequences. In the source area, these clayey gravels, generally few meters thick, appear as transformed from the underlying densely fractured mudstone/shale. Along the Chi-shan River, the clayey gravels were exposed as thick as 20 m. Tsou et al. (2011) have recognized “jigsaw structures”, typical of rock-avalanche deposits (e.g., Hewitt et al., 2008), in these gravels. We found such crushed gravels only on an abnormal, 15 m-high rounded “hill” on the left bank of the Chi-shan River (Fig. 5). The clayey gravels constituting this “hill” appear to be more compacted than their surrounding counterparts. The former also exhibits stratifications dipping to the east, against the regional valley slope (Fig. 5a).

Tsou et al. (2011) have noticed the scattering of soil clods, grass lumps and topped trees/bamboos on the landslide surfaces. They also mentioned that these toppled plants, many of which had roots still adhering to the ground, were not mixed into the underlying landslide deposits. We further found that while a great portion of these topped plants in the source area leaned downslope (i.e. with roots pointing to the upslope directions), they leaned exclusively upslope in the deposition area between Hills 578 and 560 (Fig. 6). These features suggest that the landslide involved collapsing in the source area (causing plants topping downslope) and was subject to sliding in the deposition area (causing plants slanting upslope).

Both Lee et al. (2009) and Tsou et al. (2011) have reported the abundance of angular/sub-angular giant boulders scattered on the landslide surface. We have found two such boulders that are carved by striations of multiple sets (Fig. 7). These striations, like those created underneath glaciers, were probably abraded by slowly moving, heavily loaded sediments (e.g., by heave). For multiple sets of these erosional features to be generated, either the sediments transported on the rock surfaces had repeatedly changed directions or the rock surfaces being abraded had been episodically rotated. In either case, the formation of these striations implies a complex transport history, in contrast to the simple mode of movement that emplaced the topped plants during the 2009 landslide.

5. Ancient hillslope deposits and river terraces

5.1. Ancient hillslope deposits

Most of the outcrops surrounding the Hsiao-lin landslide, from the source to the deposition areas, exhibit matrix-rich, poorly organized gravels of apparently mass-wasting origins (Figs. 8–11). These colluvial sediments are capped by woods on the tops of the sequences, and therefore must have been deposited before the 2009 event. Two types can be differentiated. The yellowish type consists mainly of
oxidized (weathered) clasts and is likely to be the product of shallow slope failures. The grayish type is composed mostly of non-oxidized clasts and is believed to be originated from deep-seated landslides with sliding surfaces cutting into unweathered materials. Many of this type of gravels, with abundant clayey matrix, resemble the prevailing brecciated mudstone gravels exhibited on the surface of the 2009 landslide.

The colluvial sediments exposed on the scarps along the headwall and northern flank of the landslide all are <20 m thick, and typically show bipartite sequences, with the coarser, yellowish type at the upper parts and the finer, grayish type at the lower parts (Fig. 8). These deposits are generally massive and dominated by angular, pebble-/cobble-sized gravels, similar to those exhibited on the adjacent landslide surface in both grain size and composition.

Along the south flank of the landslide, the colluvial gravels are 50–120 m thick, showing vague stratifications caused by segregation of beds with different colors (yellowish or grayish), grain sizes, or matrix abundance (Fig. 9). The clasts in these deposits are mainly of mudstone origin and appear to have greater degrees of roundness, and thereby longer transport distances, than their counterparts on the headwall and northern flank of the landslide. Surrounded by these sediments, a 60 m thick, west-dipping bedrock formation is exposed on a steep wall near the head of the landslide (Fig. 9a). Much of this bedrock constituting the wall is veneered with colluvial sediments. Normal
to this bedrock wall, some troughs outlined by the bedding planes and joints are developed and filled with colluvial sediments as thick as 40 m (Sites F and G; Fig. 9a, b).

The pre-2009 mass-wasting deposits also cropped out along Tributary B, below Hills 578 and 560, and on the scarp bounding the vanished Hill 590 (Figs. 10–12). Bedrock was exposed below Hill 578, forming a

Fig. 4. Profiles through the Hsiao-lin landslide (for locations see Fig. 3b). Note the change in longitudinal profile of the source hillslope from linear shape to concave-up shape.

Fig. 5. Views of a 15 m-high hill rising near the buried mouth of River A on the left bank of the Chi-shan River. (a) From the distance. Note the indistinct stratification, which dips to the bank of the river. (b) A close view of crushed gravels exhibited on the hill.
strath 100 m high above the trunk-river bed (Fig. 10a, b). Constrained by this strath, the sediments underlying Hill 578 are estimated up to 100 m thick. The lower part of this sedimentary sequence is best exposed on the north slope of Hill 578, particularly on an outcrop cut by emergency road work after the landslide (Fig. 10a). Here, above the bedrock strath and capped by a 2 m-thick sandy bed, a 17 m-thick, cobbly/bouldery gravel formation is revealed. This coarse gravel, composed of well-rounded clasts, is apparently of trunk-river origin, and its overlying sandy bed is interpreted as a floodplain overbank deposit (Fig. 11). Above this fluvial sand, at least 40 m thick mass-wasting deposits are exhibited, including two grayish formations intercalated with yellowish ones (Figs. 10 and 11). The lower grayish formation (M1), dominated by matrix-supported, subangular to subrounded pebbles/cobbles, is likely to be deposited by debris flows. The upper grayish formation (M2), a massive mud body with scattered angular pebbles, is interpreted as deposited mainly by mud flows (Fig. 11). This mud formation, up to 15 m thick, can be traced laterally over 300 m to the saddle connecting with Ridge S (Fig. 10a). There, the formation is truncated and overlain by yellowish colluvial gravels.

The mud-flow formation below Hill 578 contains fossil wood fragments, including a slanted tree (Fig. 10c). These wood materials were so well-preserved that they were sweet scented at the time being discovered. Aggregates of vivianite, a mineral typically formed in organic-rich swamp environments (e.g., Zachara et al., 1998), were also observed as adhering to the wood pieces and their surrounding clayey materials (Fig. 10d).

Ancient colluvial sediments, including both yellowish and grayish types, also are commonly observed on the hillslopes away from the Hsiao-lin landslide site (although most of them are inaccessible). An example is shown along the midstream of the Geo-pu River, where a veneer of grayish, matrix-supported debris-flow gravels with plentiful fossil woods crops out on a mudstone slope (Fig. 13a).

5.2. River terraces

Series of river terraces are developed along the Chi-shan River downstream from the gorge near Hsiao-lin Village. The widest terrace in the area, labeled WLP in Fig. 12, is located at Wu-li-pu, south of the
Terraces are generally isolated on interfluvial fans between tributaries of the Chi-shan River (Hsieh, 1999). The latter gradually decrease in height and eventually merge into the Ping-tung Plain. To the upstream direction, the WLP terrace is well correlated to the terraces that have been buried during the Hsiao-lin event. These terraces are also capped by well-rounded fluvial gravels and sands, which apparently had connected farther upstream with those exposed below Hill 578.

Terraces higher than the WLP are developed south of the Geo-pu River, rising 250–400 m above the valley bottom. These high-level terraces are generally isolated on interfluvial surfaces between tributaries of the Chi-shan River. They display two distinct steps on the southern bank of the Geo-pu River (from high to low labeled H1 and H2 in Figs. 2 and 12), or appear as single, continuously extended surfaces (as long as 2 km) farther south (labeled H in Fig. 2). Dipping oblique to and with gradients significantly greater than the trunk river, these terraces are likely to have been created by tributaries. The exposures on the H1 and H2 terraces also show 20–40 m thick, poorly stratified gravels composed mainly of subangular/subrounded clasts, which are probably of debris-flow origins. The bedrock underlying these gravels does not form strath surfaces, unlike the bedrock constituting the WLP and its correlated trunk-river terraces.

Low-level terraces 20–30 m high are also developed along the downstream reach of the Geo-pu River (labeled L in Fig. 2). New outcrops brought by Typhoon Morakot reveal that these terraces are all constituted by subangular/subrounded gravels including both the fluvial (stratified) and debris-flow (massive) types (Fig. 13b).

5.3. Radiocarbon dates

Totally 12 radiocarbon dates have been obtained, all from fossil plants (Table 1). These dates, ranging from 0 to 21 ka, show δ¹³C values around −13‰ or −27‰, typical of terrestrial plants (Table 1). This fact confirms that all the samples dated are unlikely to have been contaminated by ground water, which is rich in calcium carbonate dissolved from marine fossils in the bedrock strata, as noted by Tsou et al. (2011).

A half of the dates are derived from the road-cut exposures around Hill 578 (Sites 1 and 2; Figs. 3b, 10 and 11). The sandy bed capping the basal trunk-river gravel is dated 13450–13650 cal yr BP, from an assemblage of tiny herbaceous debris. About 4 m above, the M1 debris-flow gravel yields two dates of 13650–13860 and 13710–13880 cal yr BP from wood fragments. Farther above, a twig and a piece of bark of a trunk (Fig. 10c) within the M2 mud-flow formation are dated 11820–12090 and 12040–12380 cal yr BP, respectively. In the equivalent mud-flow formation, a date of 11980–12380 cal yr BP is derived from the saddle between Hill 578 and Ridge S (Site 2).

Near the northern flank of the landslide, an age of <0 BP is obtained from a gully cutting to a 1–2 m-thick colluvial gravel bed (Site 3; Figs. 3b and 8a). This bed, underlain by bedrock, consists of an upper, yellowish part and a lower grayish part. The date is derived from the upper part, from a small piece of wood debris within the grayish matrix. This wood debris has been compacted, distinct from the modern plant debris scattering on the landslide surface, and is believed to have been deposited before the 2009 event.

Two dates are derived from fossil wood fragments lying on the landslide surface. The one, 2890–3140 cal yr BP, is from a tree trunk collected in a gully near the head of the landslide (Site 4; Fig. 3b). The other, 21290–21540 cal yr BP, is from an assemblage of wood fragments on the sandy surface of the alluvial fan emanating from the “water slide” (Site 5; Figs. 3b and 12). These wood samples were rather fragile, and are unlikely to have undergone a long distance of transport.

In the Geo-pu catchment, a date of 14660–15080 cal yr BP is obtained from a relatively small landslide fringing Terrace H2 (Site 6; Figs. 2 and 12). The sample of this date, an assemblage of herbaceous plant fragments, was collected from a block of grayish, poorly-sorted gravel settled on the toe of the landslide. This gravel block is likely to have been eroded from a grayish-type gravel formation 10–30 m below Terrace H2, exhibited on the headwall of the landslide. Additionally, a date of 2180–2340 cal yr BP is derived...
from Terrace L along the downstream reach of the Geo-pu River (Site 7; Figs. 2 and 13b), from an herbaceous plant fragment within a gravely debris-flow bed. Finally, the wood sample within the grayish colluvial gravels exposed along the midstream of the river is dated 800–910 cal yr BP (Site 8; Figs. 2 and 13a).

6. Discussion

6.1. Source of the Hsiao-lin landslide

Instead of exhibiting steep bedrock walls typical of rock failures (e.g., Evans et al., 2007; Hewitt et al., 2008; Brideau et al., 2009), the erosion by the Hsiao-lin landslide left a rather gentle slope covered mainly by loose debris. This fact indicates that the landslide was primarily the reworking of sediments pre-stored on the hillslope. Specifically, the source materials of the landslide are those that had been transported for a significant distance, rather than in situ, fractured bedrocks as the result of weathering, tectonic damaging, or the gravitational deformation inferred by Tsou et al. (2011). This interpretation is consistent with the omnipresence of ancient colluvial deposits exposed around the source area, and is substantiated by our finding of fossil plants and striated giant boulders on the landslide surface. Based on these observations, the Hsiao-lin landslide may be classified as a debris avalanche. Note that before the landslide, the existence of thick colluvial sediments in the source area has been suggested by its poorly-drained hummocky topography. This source area had a slope of 21°–23° (Fig. 4), which is smaller than the minimum slope of 25° typical of rockslide–rock avalanche (Keefer, 1984).

A piece of evidence used by Tsou et al. (2011) to infer the rock-avalanche origin of the Hsiao-lin landslide is the appearance of “jigsaw structures” in the landslide deposits. This type of structure, a result of crushing of clasts, has been considered as typically created in a dry condition (Hewitt et al., 2008). How such structures were created during the Hsiao-lin landslide, when the surrounding condition was extremely wet, remains an issue. In fact, we found crushed gravels only on the abnormal “hill” on the left bank of the Chi-shan River. The constituents of this “hill” exhibit stratifications dipping against the valley slope and appear to be more compacted than the surrounding landslide deposits. We suspect that this “hill” is actually a block of ancient landslide deposits and that the observed crushed gravels might have been produced during an old rock-avalanche event. The emplacement of this hilly block implies that at least part of the
Hsiao-lin landslide was dominated by slides rather than the granular flows characteristic of an avalanche (e.g., Friedmann et al., 2003). This inference is consistent with the observation that the plants on the nearby landslide surface leaned exclusively upslope and were not mixed into the underlying landslide materials (Fig. 6b).

6.2. Bedrock controls on the Hsiao-lin landslide

Although many studies have considered the Hsiao-lin landslide as the dip-slope or the wedge-shaped type, the erosion by the landslide did not result in planar surfaces in a large scale. Also, judging from the shape of the hillslope and the erosion pattern of the landslide (Fig. 3a), the source area of the landslide appears to have been eroded somewhat homogeneously, which is consistent with the weakness of the underlying, densely fractured mudstone/shale bedrock. The limited bedrock exposure in the area (Fig. 3b) further reveals that the sliding plane (or planes) of the landslide was mainly in the old colluvial deposits.

On the other hand, with an increase in the thickness of sandstone strata, the bedrock exposed in the transport area of the landslide, such as along the “water slide”, exhibits distinct bedding planes. Lee et al. (2009) and Tsou et al. (2011) also have shown some east-west-trending joints/faults on the scarps fringing the north slope of Ridge S and the south flank of the landslide (Fig. 3b). These bedrock surfaces appear to have controlled the morphology (and thus the development) of the headwaters of tributaries A and B. For example, the slope fringing the “water slide” to the north, apparently a dip slope, is planar, moderately dipped, and strikes with an obtuse angle to the river axis. By contrast, the slope fringing the “water slide” to the south (i.e. along the south flank of the landslide), which probably follows the east-west-trending fault systems, is steep and nearly parallel to the river (Fig. 3b). Similar structure-controlled landforms of smaller scales are observed along the south flank of the landslide (Fig. 9b).

We have noticed that bedrock types and structures control the distinct shapes between the source and transport areas of the 2009 landslide. It is further suggested that the creation of the concave-shape slope in the source area could reflect the high erodibility of the area relative to the transport area (Figs. 3b and 4). As will be discussed later, the formation of such a landform, together with tributaries A and B in the downslope direction, could strongly affect the subsequent sediment deposition/transport, and in turn controlled the genesis of the 2009 landslide.

6.3. Long-term landscape development

Although most researchers have focused the Taiwan’s orogenic belt on the effectiveness of the erosion processes to balance the rapid tectonic uplift (e.g., Hartshorn et al., 2002; Dadson et al., 2003; Yanites et al., 2010), we found that >20 m thick ancient mass-wasting deposits are widespread in the study area. Also notable is the development of the WLP and its correlated trunk-river terraces. The presence of bedrock straths with up-to-20 m-thick fluvial sediments underlying these terraces indicates that the trunk river had maintained at a more or less constant level, or even undergone aggradation. This condition
requires that immense sediment had been supplied into the river, hinder-
ing or even reversing the long-term incision of the river in response to the tectonic uplift.

The recorded mass-wasting histories of the area can be traced back to 21 ka. Being probably short-transported, the sample of this date was most likely reworked from the vanished Hill 590 or its adjacent side ridge (around Site I; Fig. 12). An additional episode of mass-wasting activity is dated 14.9 ka from Terrace H2. The magnitude of this mass-wasting movement was apparently great, as Terrace H2 and the other high-level terraces with similar heights to the south appear to have jointly formed an extensive alluvial surface bounding the trunk river. By extrapolating the gradient of Terrace H2 down-slope, the trunk-river bed around Wu-li-pu is estimated to have been 150 m higher than the present (Fig. 14).

At least two mass-wasting events, dated around 13.7 and 12.0 ka respectively, are revealed below Hill 578. Note that the two 13.7 ka dates (13650–13860 and 13710–13880 cal yr BP), derived from the M1 debris-flow gravel, are unreasonably older than the date (13450–13650 cal yr BP) from the underlying floodplain sand (Fig. 11). It is unclear whether the two 13.7 ka wood samples were reworked from old deposits or the herbaceous sample of 13450–13650 cal yr BP was somewhat contaminated by modern carbon. Nonetheless, considering that these three dates are close, the M1 debris-flow gravel was likely to be emplaced soon after the deposition of the underlying fluvial sediments (i.e. before the incision of the trunk river that abandoned the floodplain). The fluvial sediments here can be correlated to those capping the WLP terrace. Given that the bedrock strath exhibited on the WLP is 70–80 m high above the modern river bed, we infer that since ~14.9 ka the trunk river had been incised by 70–80 m by 13.7 ka (Fig. 14). We believe that this rapid fluvial incision (≥6 cm yr⁻¹) operated mainly on unconsolidated sediments, as observed from many aggradational terraces elsewhere in the Taiwan’s mountains (Hsieh and Chyi, 2010). In other words, the 14.9 ka alluviation is likely to have resulted in deposition of sediments much thicker than those preserved on Terrace H2.

The deposition of the 12.0 ka mud formation (M2) in the study gravel-dominated setting is worth noting. We observed thick muddy sediments in the mountains of Taiwan only in lakes or swamps as a result of damming, naturally or artificially. This fact, together with the presence of vivianite minerals in the deposit, suggests that the 12.0 ka mud-flow event took place in a lake or swamp when the Chi-shan River was dammed. Judging from the wide distribution of the M2 formation, its causative landslide was likely no smaller than the 2009 event.

The extensive landslide activities ended and erosion resumed on the lower slope of the Yu-shan Range, resulting in the exposure of not only the sediments but also bedrock underlying the depositional
landforms previously created. Given that these landforms have been extensively dissected and highly stranded above the modern river bed, the erosion is likely to have proceeded for a considerable period of time, perhaps starting no more than a few thousand years after 12 ka (e.g., assuming the erosion starting at 12 ka yields bedrock incision rate of 8 mm yr$^{-1}$ around Hill 578).

On the other hand, as the source area of large mass-wasting motions, the upper slope of the Yu-shan Range is expected to have undergone erosion when the lower slope of the range was dominated by landslide/debris-flow sedimentation. It follows that the source sediments of the 2009 event were likely accumulated by minor mass-wasting processes after 12 ka (i.e. when the erosion has dominated the lower slope of the range).

![Figure 11](image1.png)

**Fig. 11.** Description and interpretation of the stratigraphic sequence exposed on the north slope of Hill 578 (see Fig. 10b for field view).

<table>
<thead>
<tr>
<th>Description</th>
<th>Interpretation</th>
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<tbody>
<tr>
<td>Yellowish gravel, rich in sandy matrix; poorly stratified, clast-supported</td>
<td>Undifferentiated mass-wasting deposit</td>
</tr>
<tr>
<td>Grayish mud, mass; scattered with angular pebbles and, occasionally, plant fragments</td>
<td>Mud-flow deposit</td>
</tr>
<tr>
<td>Yellowish gravel, dominated by angular/sub-angular pebbles/cobbles; rich in sandy matrix; poorly stratified, clast-supported</td>
<td>Undifferentiated mass-wasting deposit</td>
</tr>
<tr>
<td>Grayish gravel, dominated by sub-angular/sub-rounded pebbles/cobbles (occasionally rounded gravel) in muddy matrix; poorly stratified, matrix-to-clast-supported</td>
<td>Mainly debris-flow deposit</td>
</tr>
<tr>
<td>Yellowish/grayish sand/muddy sand; massive or horizontal laminated</td>
<td>Floodplain overbank deposit</td>
</tr>
<tr>
<td>Yellowish gravel, dominated by rounded cobbles/boulders</td>
<td>Fluvial channel deposit</td>
</tr>
<tr>
<td>Mudstone</td>
<td>Yen-shui-keng Shale</td>
</tr>
</tbody>
</table>

![Figure 12](image2.png)

**Fig. 12.** A distant view to the Chi-shan River valley (facing downstream). Foreground exhibits ancient colluvial deposits exposed on the south flank of the Hsiao-lin landslide (~100 m high) and a post-landslide alluvial fan (AF). Note a rotational scarp at Site 1 (see also Fig. 9d), a result of erosion of a side ridge, which is likely to be the place where the radiocarbon sample collected at site 5 came from. Background shows a flight of terraces and the locations of Site 6 radiocarbon date (see also Fig. 2).
of the range), filling the accommodation provided by the erosion by the former event or events. This inferred timing of the deposition is supported by the 3.0 ka date obtained near the head of the 2009 landslide. Also, the high erodibility of the mudstone/shale underlying the adjacent relatively steep slopes assures the commonness of the minor mass-wasting motions, such as the dated ~0 BP one near the north flank of the 2009 landslide. We have dated 0.9 and 2.3 ka debris flows along the Geo-pu River. We believe that at these two dates, mass-wasting motions also occurred around the source area of the 2009 landslide, causing deposition there.

6.4. Geomorphic controls on the Hsiao-lin landslide

We have noticed the difference in evolutionary history between the Geo-pu River and the hillslope where the 2009 landslide originated (hereafter the Hsiao-lin hillslope). The Geo-pu River, like many other mountain rivers in Taiwan, has long been able to deliver sediments to the trunk river, such that even though the increase in sediment supply (due to an increase in mass-wasting activity) had caused aggradation, the aggraded sediments were efficiently removed after the sediment supply reduced. So far, only a few of these aggraded sediments were preserved underlying terraces H1, H2, and L. By contrast, sediments on the Hsiao-lin hillslope appear to have resided for relatively long periods of time. This is shown by not only the deposition of the great amount of materials before the 2009 landslide, but also the preservation of up-to-120-m-thick colluvial sequence (dated as old as 21 ka) along the south flank of the landslide. We attribute this long residence time of the sediments to the poorly drained topography of the Hsiao-lin hillslope. Without being regularly flushed out by well-developed channel networks, sediments eroded from the hillslope could continue to accumulate, until the threshold for mass transport was crossed.

In fact, the commonness of poorly-drained hummocky slopes has suggested the abundance of colluvial sediments in the study area (Fig. 2). However, only those stored on the Hsiao-lin hillslope were catastrophically transported during 2009 Typhoon Morakot. We found that the greatest difference between the Hsiao-lin and the other hummocky hillslopes is that the former is connected in the downslope direction with distinct tributaries A and B (Fig. 2). We believe that the growth of these two rivers, which followed the
underlying bedrock structures as mentioned previously, played important roles on the 2009 landslide. First, the source area of the landslide could be destabilized by the headward expansion of the two rivers, which enhanced groundwater convergence (as seen on the “water slide”). Secondly, the two rivers provided routes for the landslide materials to run downslope. An implication here is that the coupled poorly-drained hummocky slopes and their downslope connection with well-developed channel systems may be a useful criterion to foresee the sites of catastrophic landslides.

In sum, a complex evolutionary history, from progressive colluvial deposition to a catastrophic failure, is suggested on the Hsiaolin hillslope. We believe that such a deposition–erosion process has repeatedly occurred in at least the past tens of thousands of years. Today, the erosion by the 2009 landslide has created a broad, concave-shape landform on the hillslope. The burial of Tributary A also has greatly decreased the efficiency of sediment transport to the trunk river, allowing the development of an alluvial fan upslope of the main depositional zone. It is expected that colluvial sediments will continue to accumulate on the hillslope until the next catastrophic failure.

7. Conclusion

The 2009 Hsiaolin landslide originated from mass reworking of ancient colluvial sediments. In addition to the direct trigger by heavy rains, this landslide was pre-conditioned by complex erosion–deposition processes controlled by the bedrock lithology/structures and their resulting landscape features. The source area of the landslide, a broad and poorly-drained slope, is underlain by densely fractured mudstone/shale, in contrast to the sandstone-based transport area. The differential erosion on these areas could create a concave-shape landform on the upper part of the hillslope, which facilitated the subsequent sediment accumulation.

It is suggested that such a concave-shape slope was eroded by large landslides like the 2009 event, and the sedimentation here was achieved progressively by minor mass-wasting processes. The amount of sediments accumulated, which determined the slope angle, could thus control the genesis of the 2009 landslide. The landslide ran along two first-order channels in the transport area, which followed old faults or joints. The headward expansion of these channels, which enhanced groundwater convergence, could destabilize the source area, and later provided routes for the landslide materials to run downslope.

Extensive landslides/debris flows had frequently occurred in the study area, as shown by the prevalence of >20 m thick mass-wasting sequences on the lower part of the hillslope, underlying terraces and small hills. These mass-wasting activities are dated 21, 14.9, 13.7 and 12.0 ka. At least the 12.0 ka event, which caused extensive mud-flow deposition, is likely to have dammed the river. It is suggested that the deposition–erosion process causing the 2009 event has repeatedly occurred on the studied hillslope, with reocurrence intervals perhaps over thousands of years.

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References


Table 1

Radiocarbon dates obtained in this study.

<table>
<thead>
<tr>
<th>Site a</th>
<th>Material</th>
<th>14C age b (yr BP)</th>
<th>Lab. No</th>
<th>Calibrated age d (cal yr BP)</th>
<th>δ13C (%)</th>
<th>Height e (m)</th>
<th>Associated sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Herb</td>
<td>11710±60</td>
<td>Beta</td>
<td>13450–13650</td>
<td>−27.6</td>
<td>120</td>
<td>Floodplain sand</td>
</tr>
<tr>
<td>2</td>
<td>Wood</td>
<td>11900±80</td>
<td>NTU</td>
<td>13650–13860</td>
<td>−27.4±0.2</td>
<td>124</td>
<td>Debris-flow gravel</td>
</tr>
<tr>
<td>3</td>
<td>Wood</td>
<td>11930±70</td>
<td>NTU</td>
<td>13710–13880</td>
<td>−28.0±0.2</td>
<td>124</td>
<td>Debris-flow gravel</td>
</tr>
<tr>
<td>4</td>
<td>Wood</td>
<td>10240±70</td>
<td>NTU</td>
<td>11820–12090</td>
<td>−29.2±0.1</td>
<td>144</td>
<td>Mud-flow deposit</td>
</tr>
<tr>
<td>5</td>
<td>Wood</td>
<td>10330±70</td>
<td>NTU</td>
<td>12040–12380</td>
<td>−26.9±0.2</td>
<td>145</td>
<td>Mud-flow deposit</td>
</tr>
<tr>
<td>6</td>
<td>Wood</td>
<td>10300±70</td>
<td>NTU</td>
<td>11980–12380</td>
<td>−27.3±0.1</td>
<td>146</td>
<td>Mud-flow deposit</td>
</tr>
<tr>
<td>7</td>
<td>Wood</td>
<td>&lt;0</td>
<td>Beta</td>
<td>27-29791</td>
<td>−25.1</td>
<td>−290</td>
<td>–</td>
</tr>
<tr>
<td>8</td>
<td>Wood</td>
<td>(2880±70)</td>
<td>NTU</td>
<td>2890–3140</td>
<td>−27.9±0.2</td>
<td>−650</td>
<td>–</td>
</tr>
<tr>
<td>9</td>
<td>Wood</td>
<td>(17950±100)</td>
<td>NTU</td>
<td>21290–21540</td>
<td>−27.3±0.1</td>
<td>180</td>
<td>–</td>
</tr>
<tr>
<td>10</td>
<td>Herb</td>
<td>12598±51</td>
<td>Wk</td>
<td>14660–15080</td>
<td>−13.4±0.2</td>
<td>120</td>
<td>Debris-flow gravel</td>
</tr>
<tr>
<td>11</td>
<td>Herb</td>
<td>2262±28</td>
<td>Wk</td>
<td>2180–2340</td>
<td>−26.4±0.2</td>
<td>10</td>
<td>Debris-flow gravel</td>
</tr>
<tr>
<td>12</td>
<td>Wood</td>
<td>930±50</td>
<td>NTU</td>
<td>800–910</td>
<td>26.9±0.1</td>
<td>20</td>
<td>Debris-flow gravel</td>
</tr>
</tbody>
</table>

a Referred to Figs. 2, 3b, 8a, 10a, and 12.
b Ages are bracketed when derived from fossil plants on the 2009 landslide surface.
c Sample number assigned at the laboratories: NTU = National Taiwan University; Wk = the University of Waikato; Beta = Beta Analytic, INC.
d Calibrated (1σ range) by the program CALIB 6.0 (Reimer et al., 2009).
e Sample height relative to the trunk Chi-shan river bed, except for sites 7 and 8, which is relatively the Geo-pu river bed.

Fig. 14. A profile of terraces H1, H2, and WLP (for location see Fig. 2). See also Fig. 12 for field view. Date for WLP is based on the data from Hill 578.


