Application of Geological Mapping Using Airborne-Based LiDAR DEM to Tunnel Engineering: Example of Dongao Tunnel in Northeastern Taiwan

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Abstract: The use of digital elevation models (DEMs) that use airborne-based light detection and the ranging technique (airborne-based LiDAR) to understand large-scale geological structures has become important in geological surveying and mapping. Taking the Dongao Tunnel area in northeastern Taiwan as the study area, this study used the airborne-based LiDAR DEM and related value-added maps to interpret the topographic and geomorphic features of the area and identify locations for geological investigation. The characteristics of the rock mass were observed on-site and revealed by excavation of the highway tunnel in the study area; they were compared with the interpreted topographic and geomorphic features to determine the potential of using 1 m-resolution LiDAR DEM in geological surveys and in the evaluation of engineering characteristics of underground rock masses. The results of this study demonstrated that the DEM accurately captured geomorphic features: the strata composed of slate and schist had distinct appearances in both the clinometric map and the hillshade map; the locations of faults, lineaments, and drainage were consistent with those observed on-site, and the positions of these features were captured more accurately than those on conventional maps. Evident microrelief features, including the distribution of scarps, erosion gullies, and mini-drainage systems provide an effective basis for interpreting a deep-seated gravitational deformation slope and for an on-site inspection for validation. The use of high-resolution LiDAR DEM to interpret geomorphic features along with geological surveys provides a more comprehensive understanding of the survey area, supporting surveys and geological mapping, revealing the locations of potential slope failures, and enabling the assessment of tunnel engineering risks.

Keywords: light detection and ranging (LiDAR); digital elevation model (DEM); topographic feature; geomorphic feature; geological survey and mapping; deep-seated gravitational slope deformation

1. Introduction

Topographical and geological investigations are essential in every stage of the life cycle of an infrastructure; these stages are the feasibility study, planning, design, construction, operation, and rehabilitation. Results of such investigations not only affect the selection of alignment and method of construction but also provide important information concerning factors that affect structural deterioration or damage and associated maintenance measures [1–4]. The enhancement of our understanding of topographic and geological information about a site where infrastructure is to be located is a critical aspect of some strategies for adapting to climate change.
The development of a landform is affected geologically by tectonic activities and the interaction between strata and the environment; the spatial distribution and characteristics of a landform, such as rivers, ridges, terraces, creeks, cliffs, or steep overhangs, are manifestations of the long-term evolution of particular geological and environmental conditions [5,6]. Topographical data are indispensible to geological mapping. Fine topographical data are frequently used to estimate the extension of different rock layers, to determine the existence of geological structures, collapsed areas or the spatial distribution of deep-seated gravitational deformation slopes and thus to provide a basis for the interpretation of the results of geological surveys.

Topographic survey and mapping techniques have advanced greatly in recent years. In particular, topographic surveys and mapping using airborne-based light detection and the ranging technique (hereafter referred to as airborne-based LiDAR surveying and mapping) use multiple echoes of light waves, which partly penetrate vegetation to obtain information about the ground geometry in the form of a large number of fine point clouds. The point clouds provide geometric information about the surface of the ground and associated objects and substantially improve the resolution of topographic data by supporting metric-level or even more refined ground elevation models, which not only improve the accuracy of the map data but also change the method of survey and mapping [7–9]. Highly precise topographical data have improved the interpretation of large-scale geological structures, processes at the earth’s surface, the associated development of landform features, and the surveying and corresponding production of geological maps [10–14].

Arrowsmith and Zielke [15] identified the tectonic morphologies of the San Andreas Fault (SAF) using a digital elevation model (DEM) with a resolution from 0.25 to 0.5 m. They identified landforms such as benches, troughs, scarps, and aligned ridges in the 15 km long portion of the south-central SAF along the southern Cholame segment to understand the recurring earthquake slip. Khajavi et al. [16] identified the dextral strike-slip principal slip zone (PSZ) of the Hurunui segment of the Hope Fault, based on a series of previously unrecognized 69 individual fault strands on a DEM that was generated using LiDAR-surveyed topographic data. Studies by Khajavi et al. and others [10,15–18] have proved that LiDAR-surveyed data can be used to map geological structures under a forest cover in detail. Many investigations have focused on the use of DEMs generated by LiDAR surveying and mapping (hereafter referred to as LiDAR DEM) to interpret the geomorphic features of landslides [19–24] and to measure the attitudes of strata [25–27] and tracking fault traces [28–32], to improve the accuracy of geological maps. However, examples of comparisons of the results of conventional field surveying and mapping with interpretations based on LiDAR DEM, or with geological features that have been revealed by underground excavation, are scarce.

In this study, Suao and Dongao in the northeastern part of Taiwan were chosen as the study area and high-resolution LiDAR DEM was used to interpret the geomorphic features and characteristics of geological units, including the main strata of slate and schist, the fault zone between these strata, and slopes with deep-seated gravitational deformation. A field investigation was performed, and data were collected following the excavation of a highway tunnel in the study area. The ground features that were obtained from LiDAR DEM and field observation were examined to investigate the topographic characteristics and their relationships with the actual geology. The potential application of the fine LiDAR DEM in geological surveying and mapping were also addressed.

2. Study Area

The study area is between Suao and Dongao in the Ilan county, northeastern Taiwan (Figure 1). Relevant background information is provided below.

2.1. Topography

The study area has a mountainous terrain; it is in the northern part of the Central Mountain Range of Taiwan. The Mount (Mt.) Dongaoling (elevation 821 m)–Mt. Hsimao
(elevation 966 m)–Mt. Dabai (elevation 1369 m) ridge line that runs the east-west direction constitutes the watershed of the main water system. The slopes on both sides of the watershed are mostly to the south and north. All the rivers other than the Wulaokeng River, which flows in approximately the northeast-southwest direction, flow north and south from the watershed to the gently sloping area on the north and south sides of the study area, before flowing eastward into the Pacific Ocean. These rivers include the Dongwulaokeng River, the Cukeng River, the Zuntoukeng River north of the watershed, and the Dongaobei River to the south of it. The slopes on both sides of these water systems are mainly eastward and westward.

Figure 1. Topographic map of the study area.

2.2. Regional Geology

Taiwan is located in the oblique convergence zone of the Eurasian plate and the Philippine Sea plate, and its major mountain ranges and strata strike mainly northeast–southwest. In the northeastern part of Taiwan, due to the expansion of the Okinawa Trough, the strata have turned east–west and, in some cases, even east–southeast. Figure 2 is a geological map at a 1/50,000 scale of an area that includes the study area. The main strata from south to north are the Dongao Schist, the Nansuao Formation, the Suao Formation, and alluvial. The Yuantoushan Gneiss and Fengshushan Amphibolite are exposed in the southwest of the study area. The late Paleozoic Dongao Schist is one of the oldest strata in Taiwan. The lithology includes graphite schist, quartz mica schist, chlorite schist, metamorphic chert, and marble. The lithology of the Eocene to Oligocene Nansuao Formation consists of mainly slate, interbedded slate, and thick metasandstone. The middle Miocene Suao Formation is mainly composed of slate or phyllite, sometimes with a thin layer of metasandstone.
The Xiaomaoshan Fault and the Houishan Fault are the main geological structures in the study area; they are boundaries between the Suao Formation and the Nansuao Formation, and between the Nansuao Formation and the Dongao Schist, respectively. The strikes of these faults are mainly west northwest–east southeast and turning northeast–southwest near the Mt. Xiaodabai. The Xiaomaoshan Fault zone has a thickness of about 30 m and is mainly composed of fractured slate. The strata on both sides of the fault zone are difficult to distinguish in the field due to their similar lithologies. The change in the thickness of exposed metasandstone is often used to estimate the location of the fault zone. The strike and thickness of the Houishan Fault zone are similar to those of the Xiaomaoshan Fault zone, but a fault gouge, as well as breccia that is composed of quartz and flint, is common in the Houishan Fault [33–36].

![Figure 2. Geological map of the study area [33,34].](image)

### 2.3. Traffic and Tunnel

The North-link Railway and Taiwan No. 9 highway (also known as the Suhua Highway or the Tai-9 highway) are the main transportation thoroughfares that connect Suao and Dongao in the study area. The North-link Railway, after passing through the Suao Township, travels south along the Cukeng River, goes through the mountainous area using the Yungchuen Tunnels and then along a tributary of the Dongaobei River to arrive at Dongao. The Suhua Highway winds along the coastal side of the mountains, passing through the Suao Formation, Nansuao Formation, and Dongao Schist before reaching Dongao. The slopes along the highway often collapse. In 2011, the Suhua Highway Improvement project was launched to construct the Dongao Tunnel through the disaster-prone sections of the mountainous area. The two industrial roads in the study area are the forest road to Mt. Dabai and the Taiwan Stone Powder Road (abandoned) along the east coast, which are related to the transportation of minerals. The Yungchuen Tunnel, the New Yungchuen Tunnel, and the Dongao Tunnel were constructed in the 1970s, 1990s,
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and 2010s, respectively [35–38]. The geological characteristics revealed by the excavation face provided the ground-truth data that were used for comparisons in this study.

3. Methods

Figure 3 shows the flow chart of this study. First, aerial photographs provided by the Aerial Survey Office, Forest Bureau, Taiwan, were used to generate a digital surface model (DSM). Ten aerial photographs taken in 2012 with a resolution of 250 mm were used to generate a 5 m-resolution DSM based on conventional photogrammetry; heights of objects on the ground and vegetation were subtracted from the DSM to obtain the corresponding DEM. Two airborne-based LiDAR DEMs, based on scans in 2015 and 2018, were collected. These LiDAR DEMs both had horizontal and vertical resolutions of 1 m and 0.5 m, respectively (A resolution of 1 m was therefore used hereafter). From these DEMs and DSM, clinometric and hillshade maps were generated for topographic analysis and the interpretation of geomorphic features in the study area, including the fault, lineament, gully, and scarp. Drainage analysis was performed using the Hydrology tool of ArcGIS. The 1/50,000 geological map of the study area published in 1997 by the Central Geological Survey of Taiwan (Figure 2) and 1/5000 geological route maps along the Suhua Highway and Taiwan Stone Powder Road provided the regional geological information about the study area. The lithology and major geological structures shown on these maps were examined. A surface geological survey, including observation of the excavated face of the Dongao Tunnel was conducted to examine the identified geomorphic features, the boundaries of the various lithologies, and the locations of major structures, such as faults and lineaments. The interpretations and observations of outcrops were compared and discussed.

This study focused on the geomorphic features that were observed and interpreted from DEMs with various resolutions, and those observed in-situ, especially at the excavated faces of the Dongao Tunnel. The interpreted and observed features were compared in detail to address the potential application of LiDAR DEM to geological mapping and the evaluation of engineering characteristics for rock tunneling.

Figure 3. Research flowchart.
4. Results

The geomorphic features that were interpreted from clinometric maps and hillshade maps generated from high-resolution airborne-based LiDAR DEMs were divided into three groups: stratum and lithology, fault-related, and scarp and slope deformations, as described below.

4.1. Lithology

Figure 4 shows the hillshade maps and the results of associated drainage analyses. The map that was generated using a 1 m-resolution DEM (Figure 4a) was obviously sharper than the one generated by a 5 m-resolution DEM (Figure 4b). On the north side of the study area, where the Suao Formation and Nansuao Formation exposed their most abundant rock, slate, the scope with a high gray value (bright) near a ridge was typically wide, indicating that the terrain near the ridge was arc-shaped; the gray value changed uniformly along the mountain ridge lines, indicating that the elevations of the ridges varied gently. On the south side of the study area, where the Dongao schist outcropped, the range of high gray values near any ridge was narrow, and the gray value along the ridge lines varied greatly, revealing the geomorphic features of the schist-based stratum with sharp ridges and large variation in elevation. The patterns of the drainage systems analyzed using the 5 m-resolution clinometric map (the dark blue part in Figure 4c) exhibited no obvious differences between the slate area on the north side and the schist area on the south side; both exhibited features of a dendritic water system. However, the drainage systems analyzed by a 1 m-resolution clinometric map, and especially the mini-drainage systems that were revealed by microrelief analysis (the purple part in Figure 4c), were much more developed in the schist area than that in the slate area. The drainage system turned in the vicinity of marble and local grid-like drainage systems were present nearby.

Figure 5 presents the 3D clinometric map, which was produced by combining Figure 4a with its corresponding DEM. The planar structure in the schist area on the south side was much more conspicuous than the slate as the main strata on the north side, and part of it could be traced from the east to the west of the study area. The dip direction of the planar structure was consistent with the direction of regional foliation, the spacing among which was greater in the amphibolite than in the schist. The planar structure and sharp ridge line reflected the characteristics of different lithological formations on the hillshade maps generated using high-precision topographical data.

![Figure 4. Hillshade maps (sunshine direction 270°) generated using 1 m- (a) and 5 m- (b) resolution DEMs and associated results of drainage analyses (c). Dark blue and purple lines are lines of drainage obtained by analyzing 5 m- and 1 m-resolution DEMs, respectively.](image-url)
4.2. Fault-Related

Figure 6 presents hillshade maps of the areas close to the Xiaomaoshan Fault and the Houishan Fault whose locations are shown in Figure 2. The maps were generated from 5 m- and 1 m-resolution DEMs, respectively. In Figure 6a, a well-extended trace can be observed across the catchment area. Most sections of the trace passed through ravines or erosion gullies and had similar dip directions (west northwest–east southeast), with similar locations of the Houishan Fault that is shown in Figure 2. Therefore, the trace was interpreted as the lineament of the Houishan Fault. In contrast, most of the Xiaomaoshan Fault on the north side, with the exception of the sections parallel to mountain valleys on the west side of the study area, cannot be identified in Figure 6a.
Figure 6. Hillshade map in vicinity of the Xiaomaoshan Fault and Houishan Fault, generated by 5 m- (a) and 1 m- (b) resolution DEMs. Sunshine direction was 315°.

Based on the dislocation of ridges, the discontinuities of lineaments (the red dotted lines in Figure 6b), and the locations of developing ravines and erosion gullies, Figure 6b plots the interpreted spatial distribution of the Houishan Fault, which is on the west side of the study area to the south of the location of the fault as it was surveyed in 1997 (Figure 2). The inferred position of the fault is plotted as a dashed line in Figure 2.

The locations of the fault in Figure 6 provided a guide for field geological surveys. Figure 7 shows the findings of the on-site investigation. A fault gouge was observed in the erosion gullies on the coast (Figure 7a,b) and the left bank slope of the Zuntoukeng River (Figure 7c,d), and the surrounding slate was very broken, confirming the interpreted fault locations.
Figure 7. On-site investigation of the Houishan Fault. Images taken near the erosion gullies on the eastern coast (a, b) and the left bank slope of the Zuntoukeng River (c, d).

4.3. Scarp and Slope Deformation

Figure 8 shows the 5 m- and 1 m-resolution clinometric maps of the vicinity of the north portal of Dongao Tunnel, along with the orthoimage that was produced by superimposition of an aerial image on a 1 m-resolution DEM. In this small area of $530 \times 500$ m, the 5 m-resolution clinometric map was quite vague, and only the outline of the river and slope could be seen on it. Micro-landform features, such as scarps and erosion gullies, were difficult to identify, as was the forest road. In the 1 m-resolution clinometric map (Figure 8b), not only the geomorphic features of the river and terraces in the orthoimage (Figure 8c) but also the vegetation could be clearly observed, the latter as the shaded part of the forest road with a width of 2–4 m. Scattered scarps and gullies were also clearly seen. Figure 8d,e plots the topographical profiles, extracted from the 1 m-resolution DEM, along the south-bound and north-bound lanes of the Dongao Tunnel. Fine topographic features, such as the erosion gullies and scarps, were clearly depicted, favoring the interpretation of the boundary of a slope with deep-seated gravitational deformation.

Figure 9 shows the slope with deep-seated gravitational deformation that is shown in Figure 8b, as it was found on site. The slate was twisted with open cleavage; collapsed debris had accumulated to form small taluses under scarps (Figure 9a). The cleavage of slate had a dip of about $30^\circ$, which was significantly lower than the high angle of the cleavage that was measured for a nearby slate. However, the site was densely planted and identifying the scope of gravitational deformation was impossible.
Figure 8. Clinometric maps with 5 m- (a) and 1 m- (b) resolution, and an orthoimage (c) near north portal of the Dongao Tunnel. Topographic profiles along the north-bound (d) and south-bound (e) lanes of the tunnel, extracted from the 1 m-resolution DEM.

Figure 9. Images taken near the boundary of a slope with a deep-seated gravitational deformation. (a) Debris piled-up to form a talus under a scarp. (b) A slate twisted with an open cleavage.
5. Discussion

Based on the geological information that was revealed by tunnel excavation, this section discusses the application of the fine geomorphic information that was obtained from the airborne-based LiDAR DEM in the geological survey and mapping.

5.1. Lithology

Figure 10 shows the 3D terrain model, digital elevation model, and images of excavated faces of Dongao Tunnel in its northern portal section. The 3D models clearly showed the erosion gullies that developed near the Xiaomaoshan Fault and the Houishan Fault. The flow paths of these gullies were obviously concentrated in the lower part of the mountain, and many bifurcations in the elevation above the belly part of the mountain were observed. In addition, the fractured geology close to the faults was conducive to the development of erosion gullies, but these erosion gullies were not necessarily the geomorphic features of a fault, as was evidenced by the existence of erosion gullies. The dislocations of ridges and the spatial distribution of gullies provided information about the location and horizontal extension of a fault, but the vertical extensibility of the fault could not be fully determined from the geomorphic features.

Figure 10c is an image that was captured during the NN177 rounding of the Dongao Tunnel, when tunneling was begin carried out in the Suao Formation, north of the Xiaomaoshan Fault. (The first and second Ns represent the north-bound lane and the north-working site, respectively; the number is the number of the rounding cycle during tunneling.) The cleavage of the slate approximately parallel to the excavated face had a high persistence, and the slate was yellowish-brown due to rust staining and frequent infilling with mud. The joint set that dipped to the east with high angles (on the left in the image) had a moderate spacing (20–60 cm), high persistence, and obvious rust staining. Joints were typically opened with filling materials. Figure 10d shows an image that was captured during the NN1020 rounding, when tunneling was being carried out in the Dongao Schist formation, south of the Houishan Fault. The greenschist was occasionally mixed with black schist with highly persistent schistosity, approximately parallel to the excavation face. Fractures in the schist were filled with mud, quartz veins, and carbonate minerals. Multiple sets of joints had moderate to wide spacing and low persistence. The uniaxial compressive strength of the slate of the Suao Formation was typically less than 25 MPa, which corresponded to a weak rock; that of the Dongao Schist was in the range of 25–50 MPa, which corresponded to a medium-strength rock. Metasandstone, which typically has a relatively high strength, was observed in a few parts of the Dongao Schist formation. The geological data obtained by the excavation of the Dongao Tunnel were consistent with the geomorphic features of the two types of strata shown in Figure 4: Slate had a low resistance to weathering. As a result of weathering, it formed flaky or broken rock masses and then gradually weathered further into soil, so the ridge lines were mostly arc-shaped. The schist had high resistance to weathering; the persistence of schistosity exceeded that of other joint sets, and the quartz veins and carbonate minerals that filled the fissures of schist were also highly resistant to weathering. The attitudes of schistosity and their appearance after weathering remained prominent geomorphic features and were captured by the fine topographic surveying and mapping using an airborne-based LiDAR.
Figure 10. 3D terrain model (a), digital elevation model (b), and images of the excavation face captured during tunneling in the slate of Suao Formation (c), the schist of Dongao Schist Formation (d), the Xiaomaoshan Fault (e), and the disturbed zone of the Houishan Fault (f).
5.2. Fault Zone

Figure 10e is an image of the Xiaomaoshan Fault that was captured right after the excavation during tunneling. Disturbed by the fault, the rock mass was severely deformed and had a low strength. A fault gouge was seen on the excavation face. The discontinuity was difficult to identify. Ring excavation with a reserved core-ground part was performed to avoid collapse of the excavated face, but significant deformation of the sidewall of the tunnel was still observed. The rock mass in the zone of the Houishan Fault was more disturbed than that in the zone of the Xiaomaoshan Fault. Before the tunnel excavation, the pipe roof method must have been used to support the surrounding ground to protect the tunnel. The excavated face was immediately covered with shotcrete to mitigate its weathering. Therefore, only the images that were taken from both sides of the Houishan Fault are available, but images from the most severely sheared section of the Houishan Fault are not. Figure 10f shows the excavation face of the Dongao Tunnel in the section that was near, and was disturbed by, the Houishan Fault. Slate interbedded with metasandstone was exposed at the excavation face. The rock mass was loosely interdispersed with mud, and quartz veins and calcite penetrated the weak discontinuity planes. Rock debris commonly fell from the excavation face following tunnel excavation.

Lin and Kao (1997, 2009) [33,34] indicated that the strata on both sides of the Xiaomaoshan Fault were difficult to distinguish in the field due to their similar lithologies, and a fault gouge and breccia that was composed of quartz and flint were indicators for the location of the Houishan Fault. Benefiting from the capability of LiDAR to partly penetrate vegetation and thus depict the ground features more realistically, we found that the zones of the Xiaomaoshan Fault and the Houishan Fault exhibited in LiDAR DEM landforms different from adjacent areas. Compared with the 3D terrain model shown in Figure 10a, the Xiaomaoshan Fault zone had a texture that was much rougher than that of the adjacent Suao Formation and Nansuao Formation (Figure 10b). Such a rough texture was obvious in the slope where the fault intersected, but not in the ridge and river side, perhaps because a rigorous erosion had eroded the local geomorphic features caused by faulting in the latter two areas. The Houishan Fault was surrounded by slate and schist on both sides. Its fault zone had developed more corroded gullies, which had severely damaged the geomorphic characteristics. The rough texture of the fault zone in LiDAR DEM could only be observed near the elevation of the quarry road, and it was no longer visible below the slope belly (Figure 10b). Nevertheless, the feature of rough texture can be an indicator for fault traces (Figure 6) and provide a basis for field investigations.

Based on the locations of the Xiaomaoshan Fault and the Houishan Fault that were interpreted from the high-resolution clinometric and hillshade maps, as well as the geological observations on-site and geological information obtained from the excavation face of the Dongao Tunnel, we plotted the lithological distribution along the tunnel and at the locations of the encountered faults, further refining the geological map (Figure 11). The tunnel excavation revealed the locations of the disturbed zones of the Xiaomaoshan Fault and the Houishan Fault, and provided information about the vertical extension of these faults. The disturbance zones of the Xiaomaoshan Fault and the Houishan Fault along the tunnel direction ranged 153–164 m and 173–177 m, respectively—close to those interpreted from high-resolution clinometric and hillshade maps (118–130 m and 102–158 m, respectively), but different from those indicated in the geological map (30 m and 60 m, respectively) that was determined using conventional methods of geological investigation, and surveying and mapping.
Figure 11. Lithological distribution along the north section of the Dongao Tunnel (a) and a refined geological map (b). Conventional geological map of a similar area is enlarged (c) for comparison.
5.3. Scarp and Slope Deformation

Figure 12a shows the interpreted results concerning the landforms in the north section of the Dongao Tunnel. The development of two erosion gullies and scattered scarps was observed. The scarp indicated by the arrow was about 236 m away from the north portal of the tunnel, with its upper apex between the south-bound lane and the north-bound lane of the tunnel. This remarkable scarp had a length of approximately 70 m and a relief of 8 m. Such features on a clinometric map were inferred to be related to a deep-seated gravitational deformation, and we checked on-site which debris was piled-up under the scarp (Figure 9). A twisted slate with open cleavage was also present (Figure 9). The north-bound lane of the tunnel was crossing the slope with deep-seated gravitational deformation about 50 m below the surface. Observation of excavated faces during tunneling revealed that closer to the scarp, the rock mass was more broken, and the weathering was greater. The Geological Strength Index (GSI) of rock mass exposed on the excavation face was reduced from 25–50 in the general sections outside the deformed slope to 10–25 within the area that was affected by gravitational deformation. Figure 12b shows the excavation face of the north-bound lane (riverside) where the tunnel was passing through the boundary of the gravitational deformation slope. The cleavage of slate was approximately parallel to the excavation face, what had an obviously stained surface. The rock mass had toppled over with a variation of dip of up to 30°, causing the opening of the discontinuity to exceed 10 cm. The south-bound lane of the tunnel (hillside) was about 30 m west of its north-bound lane and it did not pass through the gravitationally deformed slope. The GSI value of rock masses that corresponded to the section where the south-bound lane of the tunnel passed through the gravitationally deformed slope was in the range of 20–35 and differed slightly from that in both adjacent sections (25–45 in the south section and 30–55 in the north section). The image captured from the excavation face within the section adjacent to the gravitationally deformed slope revealed the staining of rock masses and the displacement of discontinuities, without any opening thereof (Figure 12c). Based on the locations of the scarps that were observed on the slope and the variations of the discontinuities of the rock masses that were exposed on the excavation face of the tunnel (Figure 12b,c), Figure 12d schematically depicts the deep-seated gravitational deformation of the slope with its possibly slipping surface. The scope in which the rock mass had a high degree of weathering and the attitude of the tilted discontinuity that were affected by the deep-seated gravitational deformation exceeded the scope in which scarps were identified in the clinometric map. The rock mass in the area adjacent to the slope that was significantly affected by a gravitational deformation might still be disturbed with a moderate shear deformation; some relatively small scarps on the slope might not have been precisely identified; or some scarps that were related to the gravitational deformation slope might have been damaged by weathering and erosion, making them unidentifiable in the high-resolution clinometric map.

Figure 12e,f shows the features of rock masses that were about 24 m and 47 m below the erosion gullies. The closeness of the excavation of the tunnel to the erosion gully was positively correlated to the degree of weathering of the rock mass that was exposed on the excavation face and, therefore, to the filling of the fissures and fractures and to the proportion of the filling that was clay. Figure 12e shows an image of the excavation face below an erosion gully in the Suao Formation. The slate had weathered to yellowish-brown, and no slickenside was observed on any joint surface. Figure 12f shows an image captured from the excavation face under the erosion gully on the northern edge of the Xiaomaoshan Fault zone. The degree of weathering of the slate was higher than that in Figure 12e; the slate was further affected by the shear displacement of the fault, and a fault gouge appeared above the excavation face. The fine topographic maps obtained using an airborne-based LiDAR supported the determination of the distribution of erosion gullies and faults. However, the engineering and geological significance of erosion gullies, their quantitative engineering characteristics, and corresponding parameters require further on-site investigation for an accurate assessment.
Figure 12. (a) Features of a rock mass under the gully and under the slope that was interpreted to exhibit deep-seated gravitational deformation. (b) Image captured from the excavation face of the north-bound lane in the tunnel under a scarp. (c) Image of excavation face at the location that corresponds to (b). (d) Sketch of rock mass deformation when the tunnel passes through the slope with deep-seated gravitational deformation. (e) Excavation face under the gully in the Suao Formation. (f) Excavation face under the gully on the north edge of the Xiaomaoshan Fault.

6. Conclusions

In this study, a high-precision and high-resolution DEM generated using airborne-based LiDAR survey and mapping technique and related value-added maps were used
to understand the topographic and geomorphic features in the vicinity of Suao to Dongao in northeastern Taiwan. A field investigation was carried out and data were obtained following the excavation of the Dongao Tunnel to yield geological information about the study area. Interpretations were compared with on-site geological observations to assess the use of airborne-based LiDAR DEM in geological survey and mapping. The following conclusions were drawn.

1. The airborne-based LiDAR DEM captures more precisely the topographic and geomorphic features of strata of the study area than do topographic maps produced using traditional aerial photogrammetry. The precise locations of geological structures, such as faults and lineaments, as well as the drainage system, can be identified accordingly. On clinometric and hillshade maps, different lithologies are distinct, as is the drainage system. Such maps therefore help in the finding of outcrops for conventional surface geological investigation.

2. High-resolution airborne-based LiDAR DEM for identifying lithological boundaries, geological structures such as faults and lineament, and drainage systems, can be combined with on-site and underground excavation-based verification, to refine geological surveying and mapping.

3. A scarp on the surface of a slope is an evidence of the deformation of the underground rock mass. However, the scope in which the rock mass has a high degree of weathering and the attitude of the tilted discontinuity may exceed the scope in which scarps on a slope are identified in a clinometric map.

4. A field investigation by a professional geologist is still the most reliable method of geological surveying and mapping for the purpose of determining the engineering significance of geological features, their quantitative characteristics and corresponding parameters. Combining information thus obtained with that inferred from a high-resolution DEM can provide a more comprehensive understanding of the geological survey, including lithological distribution, geological structure, and locations of potential instabilities of a slope, favoring the assessment of tunnel engineering risks, especially in the initial stages of engineering projects, such as a feasibility study, planning, and design.

Author Contributions: Conceptualization and methodology, P.-C.L. and T.-T.W.; investigation, P.-C.L.; writing—original draft preparation, P.-C.L. and T.-T.W.; writing—review and editing, W.L., T.-T.W., and Y.-C.H.; supervision, T.-T.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the Fourth District Maintenance Construction Office and Suhua Improvement Engineering Office, Directorate General of Highways, Ministry of Transportation and Communications, Taiwan, for supporting high resolution DEMs for subsequent interpretation. Valuable comments from Liu, Huan-Chi; kind supports of data processing by Yang, Zhong-Jin; and field investigation by Ye, Zhi-Jun, are also acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Geach, M.; Stokes, M.; Hart, A. The application of geomorphic indices in terrain analysis for ground engineering practice. *Eng. Geol.* 2017, 217, 122–140, doi:10.1016/j.enggeo.2016.12.019.
2. Zangerl, C.; Eberhardt, E.; Perzlmaier, S. Kinematic behaviour and velocity characteristics of a complex deep-seated crystalline rockslide system in relation to its interaction with a dam reservoir. *Eng. Geol.* 2010, 112, 53–67, doi:10.1016/j.enggeo.2010.01.001.
3. Ambrosi, C.; Crosta, G. Large sackung along major tectonic features in the Central Italian Alps. Eng. Geol. 2006, 83, 183–200, doi:10.1016/j.enggeo.2005.06.031.
4. Tang, H.; Li, C.; Hu, X.; Su, A.; Wang, L.; Wu, Y.; Criss, R.; Xiong, C.; Li, Y. Evolution characteristics of the Huangtupo landslide based on in situ tunneling and monitoring. Landslides 2014, 12, 511–521, doi:10.1007/s10346-014-0500-2.
5. Burbank, D.W.; Anderson, R.S. Tectonic Geomorphology, 3rd ed.; Wiley-Blackwell, United States, 2011; p. 460.
6. Radaideh, O.M.; Grasemann, B.; Melichar, R.; Mosar, J. Detection and analysis of morphotectonic features utilizing satellite remote sensing and GIS: An example in SW Jordan. Geomorphology 2016, 275, 58–79, doi:10.1016/j.geomorph.2016.09.033.
7. Dong, P.; Chen, Q. Book Review–LiDAR Remote Sensing and Applications. Photogramm. Eng. Remote. Sens. 2020, 86, 13–14, doi:10.14358/pers.86.1.13.
8. Wang, G.; Joyce, J.; Phillips, D.; Shrestha, R.; Carter, W. Delineating and defining the boundaries of an active landslide in the rainforest of Puerto Rico using a combination of airborne and terrestrial LiDAR data. Landslides 2013, 10, 503–513, doi:10.1007/s10346-013-0400-x.
9. Zhang, W.; Qi, J.; Wan, P.; Wang, H.; Xie, D.; Wang, X.; Yan, G. An Easy-to-Use Airborne LiDAR Data Filtering Method Based on Cloth Simulation. Remote. Sens. 2016, 8, 501, doi:10.3390/rs8060501.
10. Langridge, R.M.; Ries, W.F.; Farrier, T.; Barth, N.C.; Khajavi, N.; De Pascale, G.P. Developing sub 5-m LiDAR DEMs for forested sections of the Alpine and Hope faults, South Island, New Zealand: Implications for structural interpretations. J. Struct. Geol. 2014, 64, 53–66.
11. Zielke, O.; Klinger, Y.; Arrowsmith, J.R. Fault slip and earthquake recurrence along strike-slip faults—Contributions of high-resolution geomorphometry. Tectonophysics 2015, 638, 43–62, doi:10.1016/j.tecto.2014.11.004.
12. Thomas, L.; Jordan, P.; Shine, O.; Fenton, O.; Mellander, P.-E.; Dunlop, P.; Murphy, P. Defining optimal DEM resolutions and point densities for modelling hydrologically sensitive areas in agricultural catchments dominated by microtopography. Int. J. Appl. Earth Obs. Geoinf. 2017, 54, 38–52, doi:10.1016/j.jag.2016.08.012.
13. Tsao, M.-C.; Lo, W.; Chen, W.-L.; Wang, T.-T. Landslide-related maintenance issues around mountain road in Dasha River section of Central Cross Island Highway. Taiwan. Bull. Int. Assoc. Eng. Geol. 2021, 80, 813–834, doi:10.1016/j.s10064-020-01967-9.
14. Sofia, G. Combining geomorphometry, feature extraction techniques and Earth-surface processes research: The way forward. Geomorphology 2020, 355, 107055, doi:10.1016/j.geomorph.2020.107055.
15. Arrowsmith, J.R.; Zielke, O. Tectonic geomorphology of the San Andreas Fault zone from high resolution topography: An example from the Cholame segment. Geomorphology 2009, 113, 70–81, doi:10.1016/j.geomorph.2009.01.002.
16. Khajavi, N.; Quigley, M.; Langridge, R.M. Influence of topography and basement depth on surface rupture morphology revealed from LiDAR and field mapping, Hope Fault, New Zealand. Tectonophysics 2014, 630, 265–284, doi:10.1016/j.tecto.2014.05.032.
17. Barth, N.C.; Toy, V.G.; Langridge, R.M.; Norris, R.J. Scale dependence of oblique plate-boundary partitioning: New insights from LiDAR, central Alpine fault, New Zealand. Lithosphere 2012, 4, 435–448, doi:10.1130/L1201.1.
18. Lin, Z.; Kaneda, H.; Mukoyama, S.; Asada, N.; Chiba, T. Detection of subtle tectonic–geomorphic features in densely forested mountains by very high-resolution airborne LiDAR survey. Geomorphology 2013, 182, 104–115, doi:10.1016/j.geomorph.2012.11.001.
19. Lin, C.-W.; Tseng, C.-M.; Tseng, Y.-H.; Fei, L.-Y.; Hsieh, Y.-C.; Tarolli, P. Recognition of large scale deep-seated landslides in forest areas of Taiwan using high resolution topography. J. Asian Earth Sci. 2013, 62, 389–400, doi:10.1016/j.jseaes.2012.10.022.
20. Hsieh, Y.-C.; Chan, Y.-C.; Hu, J.-C.; Chen, Y.-Z.; Chen, R.-F.; Chen, M.-M. Direct Measurements of Bedrock Incision Rates on the Surface of a Large Dip-slope Landslide by Multi-Period Airborne Laser Scanning DEMs. Remote. Sens. 2016, 8, 900, doi:10.3390/rs8110900.
21. Hsieh, Y.-C.; Chan, Y.-C.; Hu, J.-C. Digital Elevation Model Differencing and Error Estimation from Multiple Sources: A Case Study from the Meiyuan Shan Landslide in Taiwan. Remote. Sens. 2016, 8, 199, doi:10.3390/rs8030199.
22. Pánek, T.; Brzézny, M.; Kapustová, V.; Lenart, J.; Chalupa, V. Large landslides and deep-seated gravitational slope deformations in the Czech Flysch Carpathians: New LiDAR-based inventory. Geomorphology 2019, 346, 106852, doi:10.1016/j.geomorph.2019.106852.
23. Görüm, T. Landslide recognition and mapping in a mixed forest environment from airborne LiDAR data. Eng. Geol. 2019, 258, 105155, doi:10.1016/j.enggeo.2019.105155.
24. Lo, P.C.; Lo, W.; Chiu, Y.C.; Wang, T.T. Characteristics of movement of a creeping slope in southeastern Taiwan influenced by river erosion and aggradation 2021. Eng. Geol. (submitted May 2021).
25. Yeh, C.-H.; Chan, Y.-C.; Chang, K.-J.; Lin, M.-L.; Hsieh, Y.-C. Derivation of Strike and Dip in Sedimentary Terrain Using 3D Image Interpretation Based on Airborne LiDAR Data. Terr. Atmos. Ocean. Sci. 2014, 25, 775, doi:10.3319/tao.2014.07.02.01(tt).
26. Yeh, C.-H.; Lin, M.-L.; Chan, Y.-C.; Chang, K.-J.; Hsieh, Y.-C. Dip-slope mapping of sedimentary terrain using polygon auto-tracing and airborne LiDAR topographic data. Geomorphology 2017, 222, 236–249, doi:10.1016/j.geomorph.2017.04.009.
27. Chang, S.-H.; Chen, C.-S.; Wang, T.-T. Sediment Sluice Tunnel of Zhengwen Reservoir and construction of section with huge underground excavation adjacent to neighboring slope. Eng. Geol. 2019, 260, 105227, doi:10.1016/j.enggeo.2019.105227.
28. Chang, K.-J.; Chan, Y.-C.; Chen, R.-F.; Hsieh, Y.-C. Evaluation of Tectonic Activities Using LiDAR Topographic Data: The Nan-kan Lineament in Northern Taiwan. Terr. Atmos. Ocean. Sci. 2010, 21, 463, doi:10.3319/tao.2009.11.17.01(th).
29. McCalpin, J.; Gutierrez, F.; Bruhn, R.; Guerrero, J.; Pavlis, T.; Lucha, P. Tectonic geomorphology and late Quaternary deformation on the Ragged Mountain fault, Yakutat microplate, south coastal Alaska. *Geomorphology* 2020, 351, 106875, doi:10.1016/j.geomorph.2019.106875.

30. Chen, R.-F.; Lin, C.-W.; Chen, Y.-H.; He, T.-C.; Fei, L.-Y. Detecting and Characterizing Active Thrust Fault and Deep-Seated Landslides in Dense Forest Areas of Southern Taiwan Using Airborne LiDAR DEM. *Remote. Sens.* 2015, 7, 15443–15466, doi:10.3390/rs71115443.

31. Kania, M.; Szczęch, M. Geometry and topology of tectonolineaments in the Gorce Mts. (Outer Carpathians) in Poland. *J. Struct. Geol.* 2020, 141, 104186, doi:10.1016/j.jsg.2020.104186.

32. Pánek, T.; Minár, J.; Vitovič, L.; Březný, M. Post-LGM faulting in Central Europe: LiDAR detection of the >50 km-long Sub-Tatra fault, Western Carpathians. *Geomorphology* 2020, 364, 107248, doi:10.1016/j.geomorph.2020.107248.

33. Lin, C.W. *Explanatory Text of the Geological Map of Taiwan-Suao Sheet*, 1st ed.; Central Geological Survey, Taiwan: 1997.

34. Lin, C.W. *Explanatory Text of the Geological Map of Taiwan-Suao Sheet*, 2nd ed.; Central Geological Survey, Taiwan: 2009.

35. Lin, Y.C.; Shen, T.Y.; Hsian, S.C.; Shau, H.J. Case study on the geological characteristics and collapse of the weak intercalation of schist at the Dongao Tunnel in the Suhua Improvement Engineering Project. *Sino-Geotech.* 2017, 151, 35–44.

36. Lo, P.C.; Lo, W.; Wang, T.T.; Chiu, Y.C. Geological Characteristics of Tunnel Surrounding Rocks in Heavily Deformed Ground: Case Study of Dongao Tunnel, Taiwan. In Proceedings of the 5th ISRM Young Scholars’ Symposium on Rock Mechanics and International Symposium on Rock Engineering for Innovative Future, Okinawa, Japan, 1–4 December 2019; ISRM-YSRM-2019-114.

37. Wang, T.-T.; Jeng, F.-S.; Lo, W. Mitigating large water ingresses into the New Yungchuen Tunnel, Taiwan. *Bull. Int. Assoc. Eng. Geol.* 2011, 70, 173–186, doi:10.1007/s10064-010-0311-1.

38. Lin, C.S.; Shao, H.J.; Chen, Y.P.; Wang, T.T. Response of tunnel surrounding rocks in heavily deformed ground: Case study of Dongao Tunnel, Taiwan 2019. In Proceedings of the 2019 World Tunnel Congress, Naples, Italy, 3–9 May 2019.