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[Paper]

DInSAR Technique and Laser Scanning Technology and Their Utilizations in Rock Engineering and Natural Disaster Management and Prevention

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Keywords
DInSAR, drone, laser, slope, rock engineering structures, natural disaster prevention, tsunami boulders, cliff failure, sinkhole formation

Introduction

The utilization of remote sensing techniques, such as SAR-based (synthetic-aperture radar) techniques, drones, and lasers, and contact type monitoring techniques are now well-advanced. DInSAR (differential SAR interferometry) is an efficient remote sensing technique to evaluate ground deformation resulting from earthquakes, landslides, and subsidence due to groundwater withdrawal, mining, or tunnelling. It is a very effective method for evaluating ground movements over wide areas, and we have been exploring the possibilities for utilizing this technique in geotechnical and disaster prevention issues in the Ryukyu Archipelago.

Drones and laser scanning technologies are quite advanced, and they are now utilized in many engineering projects. Furthermore, they may be utilized for the long-term monitoring of rock engineering structures for maintenance purposes. The authors have been utilizing drones and laser scanning technology for the quantification of landslides and failure of bridge foundations induced by natural causes such as earthquakes. Furthermore, the authors have been utilizing drone and laser technology to evaluate the geometry, size, and position of tsunami boulders on Okinawa Island, Ishigaki Island, Shimoji Island, and Miyako Island to estimate the possible magnitude of mega-earthquakes in the Ryukyu Archipelago (Aydan 2018). Furthermore, this technology is used to evaluate some slope failures caused by heavy rainfalls and the topographical situation of cliffs on various islands, such as Miyagi Island.

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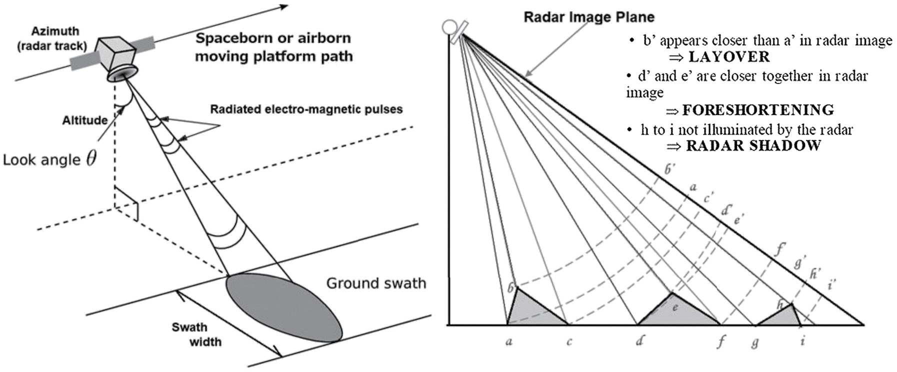
In this study, the authors briefly introduce the principles of DInSAR, drone, and laser scanning technologies. Then, several utilizations of these techniques for actual events such as slope failures, sinkholes, and tsunami boulders are presented. In addition, some examples of the utilization of these techniques in assessing some landslides, cliff failures, and long-term monitoring of deformation of bridge foundations are presented. Furthermore, it is shown that these techniques can be effectively used for assessing such situations and taking prompt actions in the Ryukyu Archipelago to deal with natural disaster management and prevention.

Radar, Synthetic-Aperture Radar, and its Derivatives

Radar is fundamentally based on the principle of radiated electro-magnetic (EM) waves and received reflected electro-magnetic waves in their place of origin. The speed of EMs is equal to the speed of light. Since the speed is constant, it allows us to compute the distance between the radar site and reflected objects by measuring the running time of transmitted pulses. The path of EMs is fundamentally straight, and it is slightly affected by atmospheric and weather conditions. It also allows us to compute the azimuth and elevation of the reflected objects. Coherence is an important parameter in radar imaging, and it indicates the phase relation between the transmitted and received electromagnetic waves. Oscillation and electromagnetic waves are coherent if their phase relationships are constant.

A synthetic-aperture radar (SAR) is an imaging radar mounted on an airbeorn or spaceborne moving platform (fig. 1*A*). It transmits EMs sequentially, and the echoes are collected and digitized and stored for processing. As transmission and reception of EMs occur at different times, they are mapped to different positions. The well-ordered combination of the received signals results in a virtual aperture. It is therefore called "synthetic aperture" imaging radar. The range direction is parallel to the flight track and perpendicular to the azimuth direction. SAR utilizes the amplitude and the absolute phase of the backscattered radar signal. A SAR system transmits electromagnetic waves at a wavelength that can range from a few millimeters to tens of centimeters. The amplitude image records yield information on the terrain slope and surface roughness, while the phase image records information on the distance between the satellite and the Earth's surface.

Since the reflected signals of the electromagnetic waves are affected by the topography and objects on the ground surface, foreshortening and shadows occur in reflected signals (fig. 1*B*). Layover occurs when the radar beam reaches the top of a tall feature before it reaches the base. Layover effects on a radar image look very similar to effects due to foreshortening.



A

B

FIGURE 1*A*. Main principle of a moving platform radar, and *B*. Geometric distortions in radar imaging (Curlander and McDonough 1992).

Interferometry Synthetic-Aperture Radar (InSAR) utilizes the differential phase of two or more SAR images along the same trajectory. It is used to identify surface movements through time, and it is a radar technique for geodesy and remote sensing. The technique can measure millimeter-scale changes in deformation over spans of days to years. It has been applied in the monitoring of natural hazards, such as earthquakes, volcanoes, and landslides; mining induced subsidence and sinkhole formation; as well as the monitoring of linear, long structures such as long-span bridges.

Differential interferometry synthetic aperture radar (DInSAR) utilizes two SAR images of the same area acquired at different times. If the distance between the ground and satellite changes between the two acquisitions due to surface movement, a phase shift occurs. DInSAR is a tool to identify progressing movement. Differential interferometry, or DInSAR, is interferometry itself. The only difference is that topographic effects are compensated for by using a Digital Elevation Model (DEM) of the area of interest, creating what is referred to as a differential interferogram. As an example of the utilization in the Ryukyu Archipelago, the SAR images of C-band obtained by the Sentinel 1 satellite during 2016/4/30 and 2019/9/12 were used to analyze the deformation of the east slope of the Nakagusuku area of Okinawa Island and figure 2 shows the results of the DInSAR analysis. Some areas with large deformations are noted, and these areas may correspond to potential landslides. In particular, this type of analysis may also be useful to identify potential landslide areas and to concentrate the detailed monitoring results and the actions to be taken against geotechnical disasters.

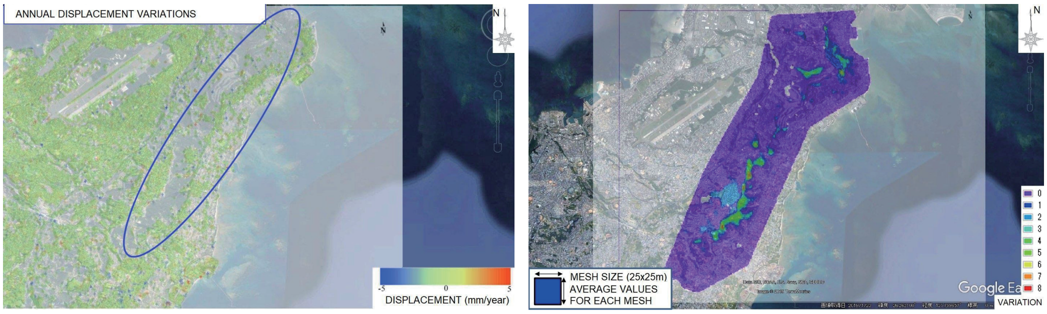


FIGURE 2. Results of DInSAR analysis.

Principles of Drone and Laser Technologies

Drones are essentially unmanned aerial vehicles (UAV) equipped with high-quality cameras, which can take photos at exact intervals, and with gyroscopes, an inertial measurement unit (IMU), and controllers to fly smoothly. For perfect flying of a drone, the IMU, gyro stabilization, and flight controller technology are essential (fig. 3*A*). Drones generally use three and six axis gyro stabilization technology to provide navigational information to the flight controller. An IMU detects the current rate of acceleration using one or more accelerometers. A magnetometer may be used to assist the IMU on drones against orientation drift. Drones may be equipped with a number of sensors, such as distance sensors (ultrasonic, laser, lidar) and chemical sensors, for digital mapping or other purposes. Since lidar, which is an acronym for laser interferometry detection and ranging, can penetrate forest canopy, it is widely used for topographical mapping.

The basic principle is based on the emission of a light signal (laser) by a transmitter and the reception of the return signal by a receiver. The scanner uses different techniques for distance calculation that distinguish the type of instrument in the receiving phase. The distance is computed from the time elapsed between the emission of the laser and the reception of the return signal or phase shift based on when the computation is carried out by comparing the phases of the output and return signals. The laser scanner devices operate by rotating a pulsed laser light at high speed and measuring the reflected pulses with a sensor (figs. 3*B* and *C*). The scanner automatically rotates around its vertical axis, and an oscillating mirror moves the beam up and down. The scanner calculates the distance of a measured point together with its angular parameters. The measured points constitute a set of points called cloud points, which are used to quantify the geometry of the structure or surface in 3D.

A. Drone B. Laser Scanner C. Hand-held scanner

FIGURE 3. Views of the utilization of a drone and laser scanners in the Ryukyu Archipelago.

Utilizations in Rock Engineering in the Ryukyu Archipelago

A. Utilization of Drones for Surveying Cliffs and Steep Slopes

Investigation of the possibility of the failure of slopes and cliffs or the back analysis of already failed cliffs and slopes requires exact geometry of the topography. Figures 4 and 5 show the applications of drone technology along the shore of Gushikawa in Itoman City in the south of Okinawa Island and the shore in the southern part of Miyako Island. As noted from the figures, it is quite easy to digitally evaluate the geometry of slopes and cliffs. Without such technology, the evaluation of cliffs is particularly cumbersome and dangerous due to overhanging rock mass with toe erosion.

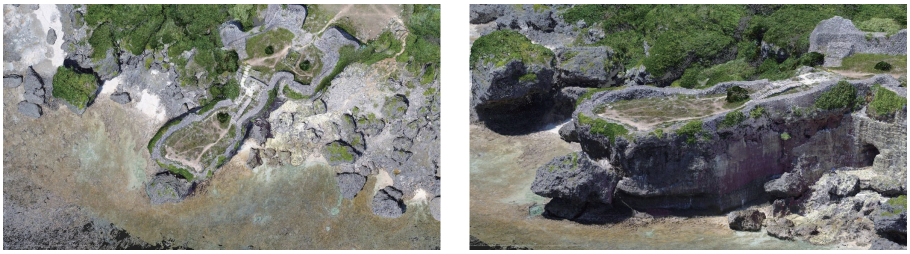


FIGURE 4. Digital images of the cliffs in the vicinity of the Gushikawa Castle remains in Itoman City.

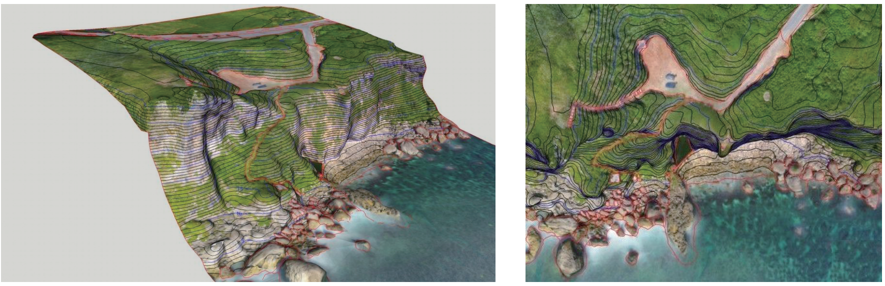
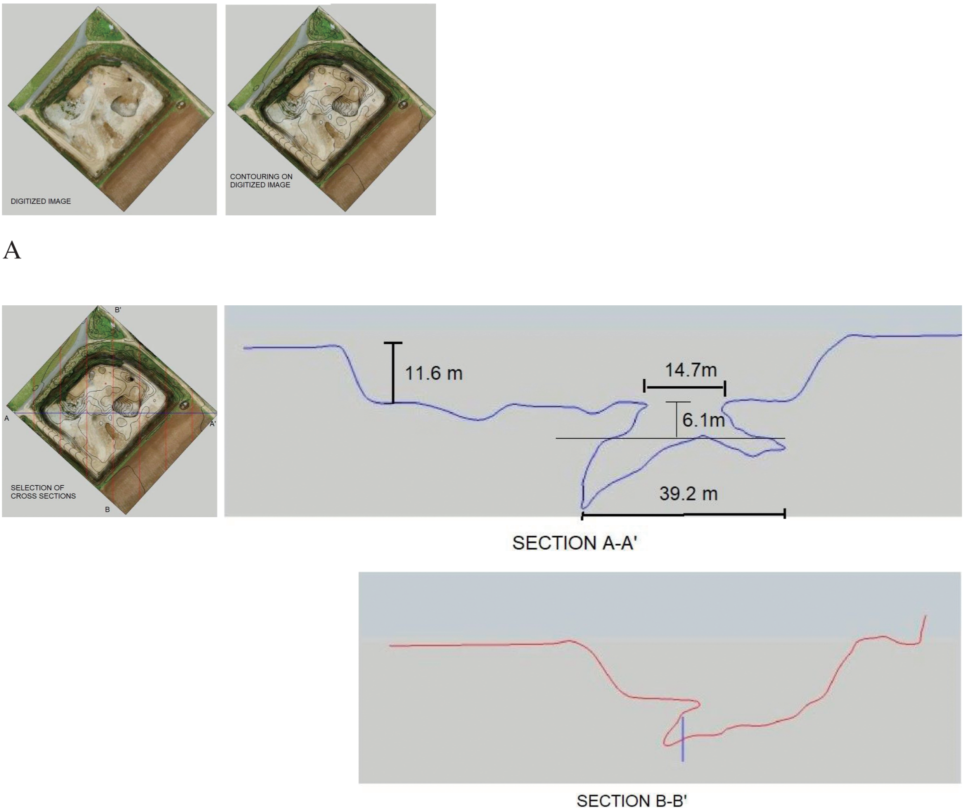


FIGURE 5. Digital images of the cliffs on the southern shore of Miyako Island.

B. Utilization of Drones for Surveying Sinkholes

The evaluation of the geometry of sinkholes is an extremely difficult and dangerous task due to their unstable configuration and unseen cracks. A sinkhole recently occurred in a Ryukyu limestone quarry on Kumejima Island during quarrying. An excavator fell into the sinkhole together with its operator. Luckily, no one was hurt. The authors were consulted by the owner of the quarry to carry out an evaluation of the size and geometry of the sinkhole. A drone utilizing the aerial photogrammetry technique was employed at this site, and the results are shown in figure 6. It is interesting to note that the overhanging part of sinkholes can be accurately evaluated.



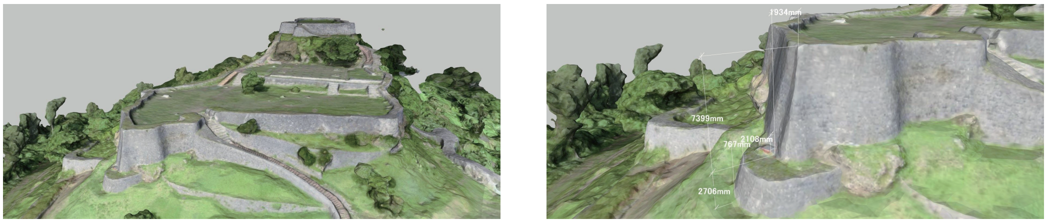
A

B

FIGURE 6*A*. Evaluation of the sinkhole geometry; *B*. Selected cross-sections.

C. Utilization of Drone Technology for Evaluating Historical Masonry Structures

There are many historical masonry structures in Okinawa Prefecture, Japan. The northeast corner of Katsuren Castle collapsed during the 2010 Off-Okinawa Island Earthquake. Therefore, there is great concern about the performance and stability of masonry structures during both earthquakes and long term in Okinawa Prefecture. The authors have been involved with the Katsuren Castle and Nakagusuku tunnel, where the authors have been carrying out long-term monitoring and strong motion observations (fig. 7 and 8). The authors utilized the drone-based aerial photogrammetry technique to observe the current state of Katsuren Castle and Nakagusuku Castle, with particular attention to locations where continuous measurements were undertaken. These measurements are going to be repeated and compared with those from continuous monitoring results. The repetion of measurements using aerial photogrammetry is expected to provide the overall behavior of the castles three-dimensionally over the long term.This type of monitoring would also be the first of its kind in the world to utilize drone technology.



A

B

FIGURE 7*A*. A 3D digital image of Katsuren Castle; *B*. A 3D digital image of Katsuren Castle at its NE corner, where continuous monitoring has been implemented.

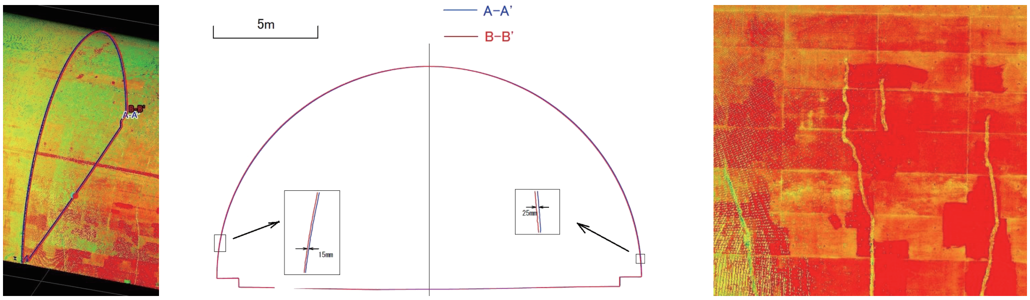
FIGURE 8. A 3D digitized image of Nakagusuku Castle.

D. Utilization of Laser Technology for Monitoring Underground Structures

As an application of laser technology for monitoring underground structures, the authors have tried to evaluate the performance of a tunnel and a large-scale arch structure in Okinawa Prefecture. Figure 9 shows a digital image of the tunnel during the construction phase. As tunnels have concrete liners added in the final stage of construction, it would be quite practical to evaluate the configuration of the tunnels in 3D digital form and to check for geometrical changes every five years. This would provide a quick evaluation of the state of the tunnel and possible locations where some degradation of support systems may have occurred. In addition, some unusual fracturing or deformed configurations of the liners resulting from large deformation or fracturing of the surrounding ground can be assessed. The concept described in the previous structures could also be utilized for the maintenance and long-term deformation monitoring of rock engineering structures such as tunnels, slopes, and underground power houses.

FIGURE 9. Laser scanner and a digital image of a tunnel under construction obtained by laser scanning.

Underground structures are sometimes built in sections in order to allow relatively large displacements and for parts to move independently from each other due to ground conditions (fig. 10*A*). Figure 10*B* shows an example of the evaluation of relative displacement between two reinforced concrete arch structures. This type of evaluation can be useful in monitoring how the blocks moved relative to each other, and it can be used to evaluate the long-term relative motions between the blocks of a reinforced concrete arch structure. Furthermore, the cracking of concrete liners due to thermal contraction or other causes might occur. High-resolution laser-scanning technology should also allow us to see if crack propagation is taking place or not. Figure 10*C* shows a laser-scanned image of a concrete liner with cracks visible.



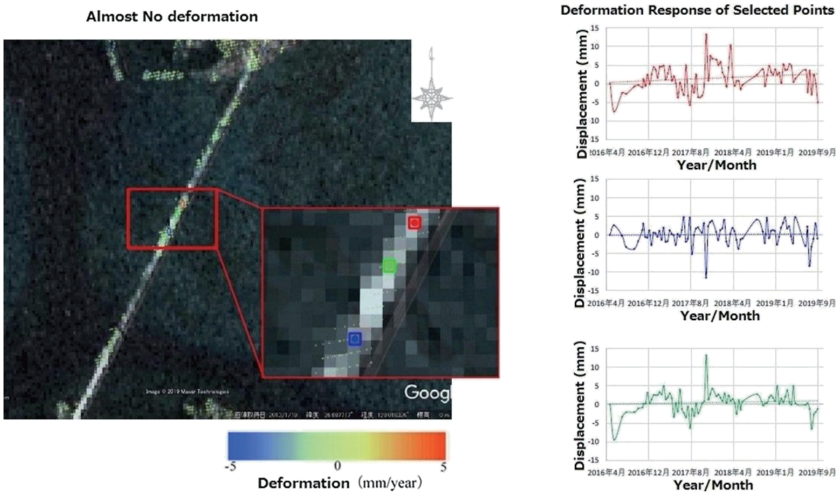
A. A joint. B. Relative movement between blocks. C. Cracks in concrete liner.

FIGURE 10. Results of laser-scanning of a reinforced concrete arch structure.

E. DInSAR Technology for Monitoring of Kouri Bridge

There is a construction example in Okinawa Prefecture that the foundations of important structures such as bridges and tanks are not fixed on/into Ryukyu limestone formations due to the possibility of karstic caves beneath them. As a result, this design philosophy places a tremendous burden on the cost of the structures. Kouri Bridge, which is 1,960 m long, was built over a Ryukyu limestone formation having a thickness of 90–120 m. Bridge construction started in 1997 and was completed in February 2005. There was concern about settlement of the piles of the piers of the bridge. Sentinel SAR images taken between the period of April 2016 and September 2019 were utilized for assessing deformation of the bridge piers. Figure 11 shows a view of the bridge and time-series data for the selected time span. As noted from the figure, there was no settlement of the bridge itself, and this fact clearly illustrates the necessity of changing the design philosophy adopted in Okinawa Prefecture concerning structures built over Ryukyu limestone formations.

A. A view of the Kouri Bridge.



B. Selected points and their time-series data.

FIGURE 11. A view and time-series data of selected points obtained from SAR images.

F. Ground Subsidence Evaluation Utilizing an Integrated Monitoring System

As mentioned in the introduction, integrated utilization of SAR, drone, and laser technologies together with contact type instrumentation for monitoring structures is desirable. The first implementation of this concept was done at a site where long-term subsidence of the ground was observed. At this site, Sentinel SAR images, laser technology, and contact type monitoring were utilized in an integrated manner (fig. 12). One of the important merits of DInSAR technology is that there is fundamentally no necessity to install instruments at the site. At this site, SAR images taken between the period of April 2016 and September 2019 were utilized for settlement evaluation. At the same site, laser measurements were taken, and it was found that about 100 mm of settlement had taken place since it was built in 1999. However, the settlement rate was quite high in recent years. For example, the contact type displacement was 8 mm during the period of January to December 2019. As this example shows, the integrated utilization of DInSAR, laser, and contact type monitoring technologies is quite promising.

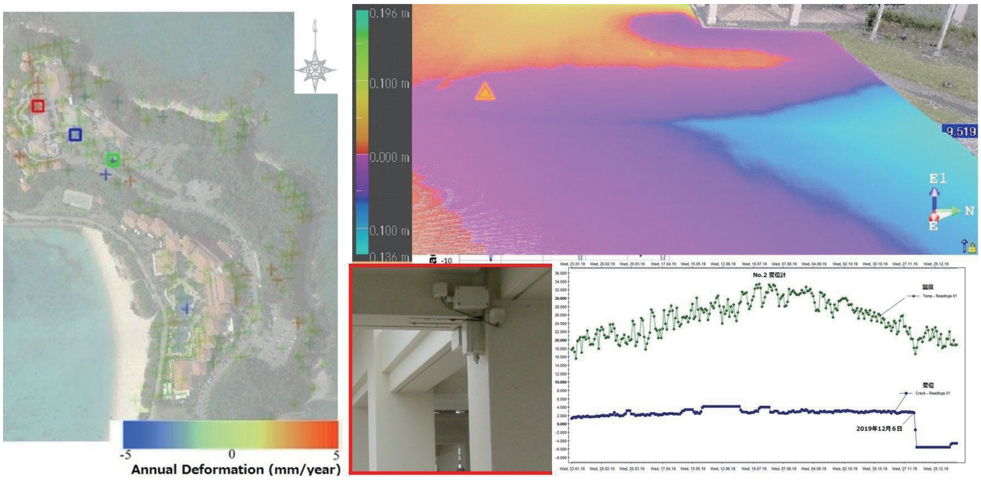


FIGURE 12. The integrated utilization of DInSAR, laser, and contact type monitoring technologies at a settlement site.

Utilizations in Natural Disaster Management and Prevention

A. Tsunami Boulders and Their Implications for Inferences about Paleo Mega-Earthquakes

There are many giant tsunami boulders on major islands of the Ryukyu Archipelago (Aydan and Tokashiki 2019). The largest tsunami boulder in the world is probably the one on Shimoji Island near the Shimoji airport. The quantification of the geometry and position of such boulders is of great importance in assessing the paleo mega-earthquake and tsunami events in a region. Drones employing aerial photogrammetry or laser scanning have been used to evaluate the tsunami boulders on Okinawa Island and Shimoji Island.

Kasakanja Tsunami Boulder on Okinawa Island. Drone-based aerial photogrammetry was utilized to evaluate the geometry and the position of the tsunami boulder at Kasakanja on Okinawa Island. Figure 13 shows the 3D topography of the investigated area together with projections of a chosen cross-section and in plan. The skill of the operator is also important when investigations are carried out in areas where overhanging cliffs exist. As seen in figure 13, the geometry of the overhanging cliffs can also be accurately evaluated.

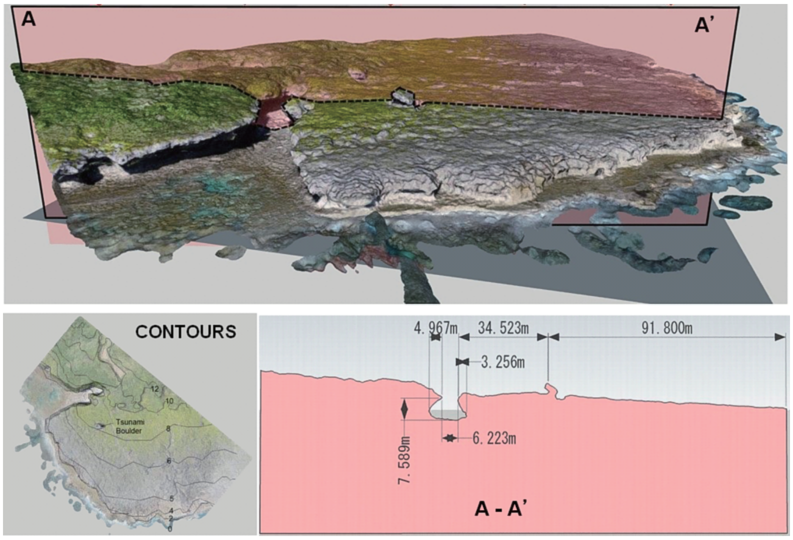


FIGURE 13. The processed digital topography of the Kasakanja tsunami boulder and its close vicinity.

The Tsunami Boulder on Shimoji Island. As mentioned previously, The Shimoji airport, with a 4 km-long runway, exists near this tsunami boulder. Since drones are resitricted from flying near airports, the ground-based laser scanning technique was used. Figure 14*A* shows the actual tsunami boulder, and Figure 14*B* shows the laser-scanned image of the boulder from the same angle. Although the laser scanning technique can evaluate the geometry of the tsunami boulder, it is somewhat affected by trees and bushes. In other words, they disturb the digital data and interfer with a proper evaluation of the geometry of the tsunami boulders.

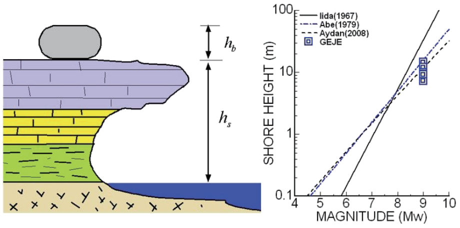

A B

FIGURE 14*A*. A photo of the tsunami boulder on Shimoji Island; *B*. A digital laser-scanned image of the tsunami boulder.

The Tsunami Boulder on Ishigaki Island. There are many tsunami boulders along the shore of Ishigaki Island. However, it is sometimes difficult to differentiate them from those boulders that have fallen onto the reefs due to toe-erosion induced by sea waves. Among them, a boulder in the Ohama District of Ishigaki Island on an elevated terrace was definitely upthrown over the terrace by a paleo mega-tsunami in the past (fig. 15). The situation of this tsunami boulder was also evaluated using ground-based laser-scanning technology.

FIGURE 15. Aerial view of Ohama District and views of the tsunami boulder and its original location.

Inferences of Paleo Mega-Earthquakes in the Ryukyu Archipelago from Tsunami Boulders. As described in the previous sub-sections, huge tsunami boulders exist in the Ryukyu Archipelago, and they may be used to estimate the magnitude of potential causative mega-earthquakes. Aydan and Tokashiki (2019) devised a method for such a purpose, and they compared their estimations with the results from other independent studies. As seen in figure 16, a mega-earthquake with a magnitude greater than 6 is likely to have taken place in the vicinity of the Ryukyu Archipelago. The moment magnitude of mega-earthquakes estimated from the tsunami boulders may range between 8.6 and 9.7.



Estimated Magntitude of Mega Earthquakes

Location	Elevation (m)	Block Height (m)	Mw (Lower)	Mw (Upper)
Shimoji	**12.5**	**9.0**	**9.0**	**9.5**
Ishigaki	**8.0**	**5.9**	**8.6**	**9.1**
Miyako	**20**	**4.0**	**9.5**	**9.7**
Okinawa	**12**	**3.0**	**9.0**	**9.2**

FIGURE 16. Inferred magnitudes of mega-earthquakes from tsunami boulders in the Ryukyu Archipelago.

B. The Assessment of Giant Rockfalls on Miyagijima from the Viewpoint of Natural Disaster Management and Prevention

Miyagi Island is east of Okinawa Island and connected through bridges to the main island. The geology consists of Ryukyu limestone on top and intercalated sedimentary rocks such as sandstone and mudstone beneath. The mudstone and sandstone layers are particularly prone to weathering. As a result, there are many overhanging Ryukyu limestone cliffs due to differential weathering of the mudstone and sandstone layers. Furthermore, Miyagi Island is shaped by normal faults, and it has a triangular shape in plane.

DInSAR analysis clearly showed that some movement along the cliff has been occurring (fig. 17*C*). A site investigation showed that there are open cracks at the crest of the cliff. The estimated thickness of the Ryukyu limestone formation is about 18–22 m at the site. Cracks are now mapped (fig. 18*B*) using a portable GPS (Global Positioning System) device with the support of an RTK (Real-time Kinematic) station on the grounds of the University of the Ryukyus (fig. 18*A*). It was decided to carry out some detailed investigations and analyses. For increasing the accuracy of SAR images at the cliff site, a marker station was established (fig. 18*D*).

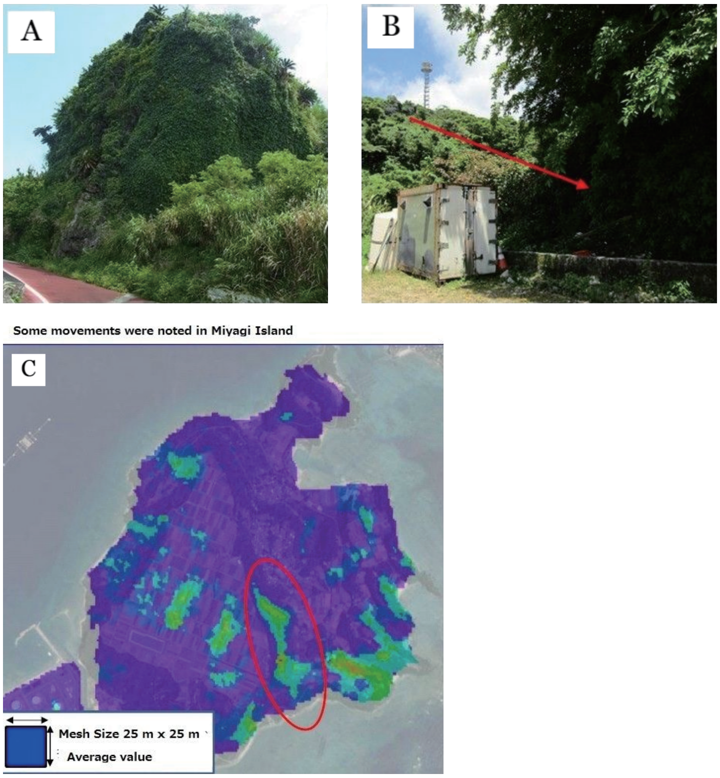


FIGURE 17*A* and *B*. Views of boulders in Miyagijima Village; *C*. DInSAR analysis.

A portable laser-scanning device was utilized to evaluate the condition and the geometry of the cliff (fig. 18*C*). Figure 19 shows the scanned image of the cliff shown in figure 18*C*. Despite very undesirable conditions for scanning, the geometry of the cliff was clearly obtained. The areas that cannot be scanned appear as dark areas in the images. Some of these dark areas correspond to cavities in the Ryukyu limestone formation. The height of the cliff was approximately 18 m high, which roughly corresponds to the thickness of the limestone formation. Furthermore, the erosion depth was up to 4 m.

A. RTK B. Crack mapping C. Laser Scanning of the cliff D. Marker

FIGURE 18. Views of RTK, crack mapping, laser scanning of the cliff and the marker for SAR.

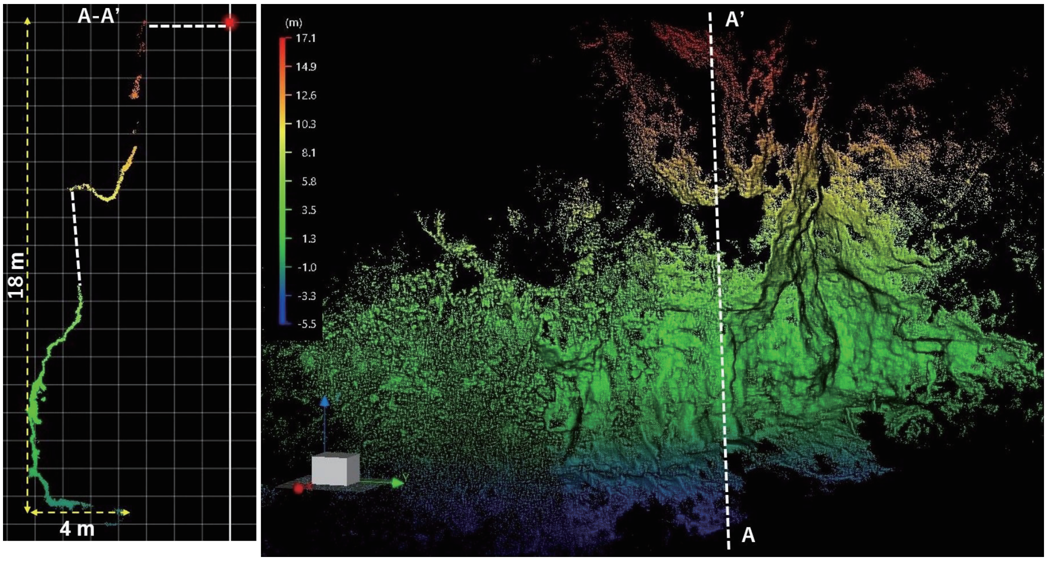


FIGURE 19. Scanned image of the cliff beneath the marker shown in figure 16*D*.

During the site investigation, we noticed a cavity in the sandstone formation beneath the limestone formation, and this site was approximately 15–20 m north to the cliff with the marker. This site is particularly important for illustrating the fundamental mechanism of cliff failure. The differential weathering of the sandstone layer beneath the limestone layer was the main cause of the bending rupture of the limestone above and the subsequent formation of a huge rock block, which is prone to toppling. The cavity was also mapped, and the images of the underground opening and cliff were matched to get a 3D image as shown in figure 20. The erosion depth of the underground opening was also about 4 m.

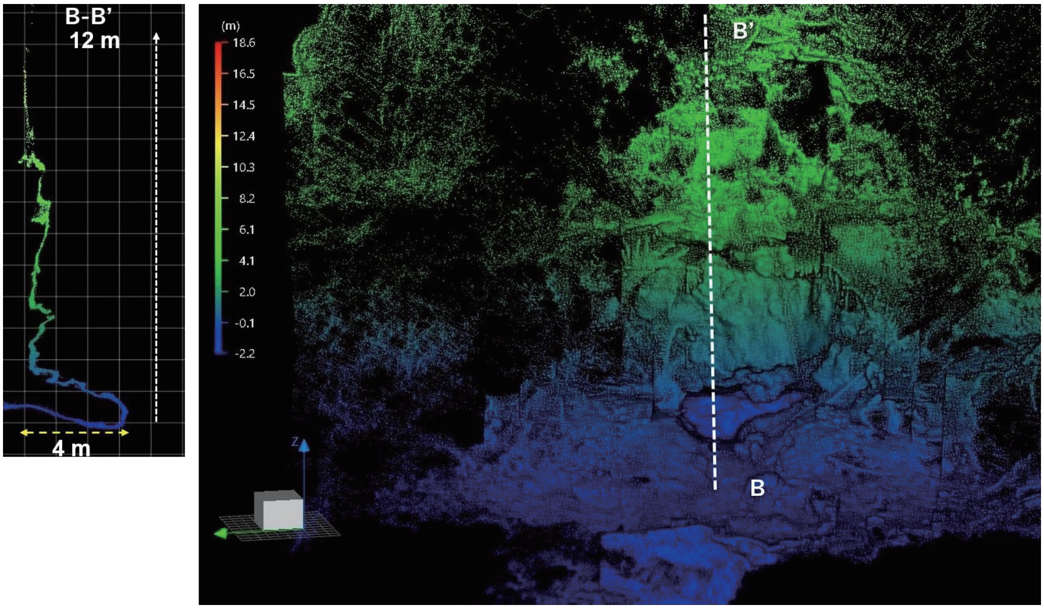


FIGURE 20. Scanned image of a cliff with an underground opening at the toe region.

Figure 21 shows a 3D and cross-section of another site scanned using an unmanned helicopter scanner where the enlargement of a roadway is planned. As can be seen from this figure, the cliff and slope beneath the limestone layer were clearly evaluated, which may be used for stability assessments.

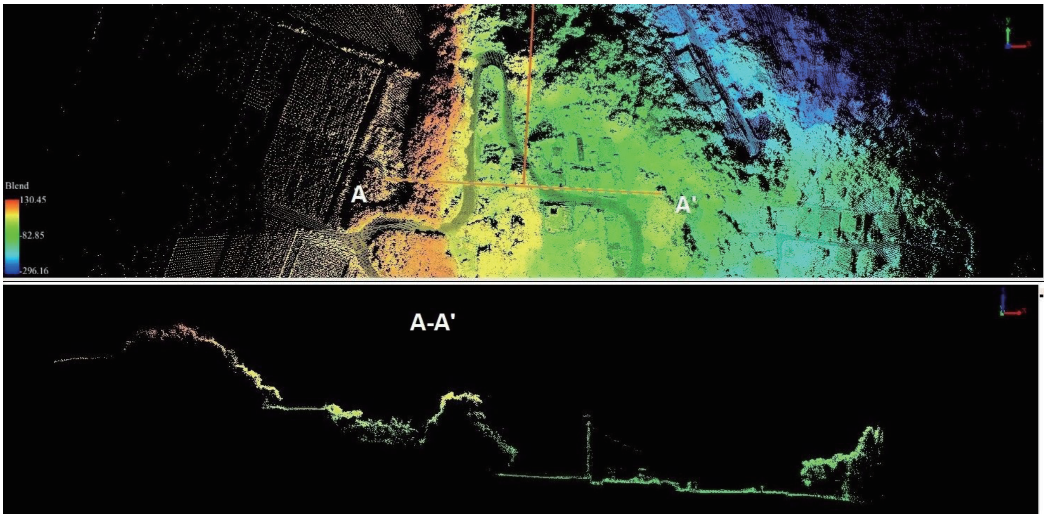
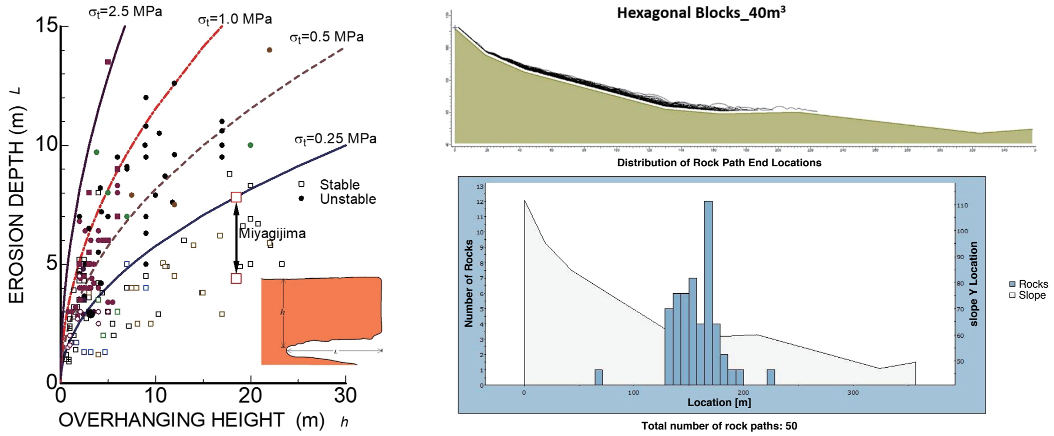


Figure 21. Image of a cliff by unmanned helicopter-based scanning device and its cross-section.

Another important issue at Miyagijima is the possibility of breakage of cliffs due to differential weathering. Site investigations indicated that erosion depth is more than 4 m and less than 7 m. Besides gravity, heavy rainfall and/or earthquakes may impose lateral forces to induce cliff failures. Figure 22*A* shows the possible stability range for the Miyagijima cliffs for different tensile strengths of the Ryukyu limestone layer. It is very likely that the cliffs would be unstable under gravitational forces if the erosion depth is greater than 7.8 m for the given cliff height and the observations on the cliffs reported by Tokashiki and Aydan (2010). Figure 22*B* shows the travel distance of hexagonal-shaped rock blocks if a rockfall is initiated (Tunar-Özcan et al. 2021). It is very clear that the people in the village of Miyagijima are under great threat of rockfalls from the cliff. Therefore, some actions and countermeasures must be immediately activated against the possibility of rockfalls.



A. B.

FIGURE 22*A*. Stability chart for cliffs on Miyagijima; *B*. travel distance of falling rock blocks.

Conclusions

Some conclusions from this study concerning the utilization of DInSAR, drone, and laser technologies in rock engineering and natural disaster management and prevention are as follow:

1) The quantitative evaluation of the post-failure state of failed structures such as slopes, cliffs and masonry structures can be easily and quickly evaluated using these technologies.
2) These technologies can be easily used in locations where human-based measurements may be unsafe.
3) Long-term monitoring of structures is possible, and it provides better assessment and evaluation of the deformation response of structures as compared with point-wise measurements.

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