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# Smart Compass-Clinometer: a smartphone application for easy and rapid geological site investigation

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## Abstract

This studypresents a smartphone application for geological site investigation. The application allows a smartphoneto replace a diverse array of instrumentation and processesrequired fordata measurement, visualization, and analysis. This application, named Smart Compass-Clinometer, consists of a digital compass-clinometer module, a data visualization module, a data analysis module, and a data management module. The compass-clinometer module measures the orientation of geological structures using data collected from built-in sensors. It converts the sensor data to orientation informationusinganalgorithm developed specifically for this purpose. The visualization module plots the measured data on stereographic projectionsusing three different methods, and can be used concurrently with the compass-clinometer module. The analysis module conducts instability analyses on themeasured data, and can present the results ingraphical andstatistical forms. Users can send or receive data wirelessly with the data management module, even without a connection to a cellular network. To evaluate and validate the precision and accuracy of the compass-clinometer module, indoor and outdoor tests were conducted using Smart Compass-Clinometer and a conventional compass-clinometer.The minimum standard deviation of measured valueswithSmart Compass-Clinometerwas 0.096° for dip and 0.122° for dip direction. The average difference between values measured using Smart Compass-Clinometerand the conventionalcompass-clinometerin the outdoor test was 1.70° for dip and 2.63° for dip direction. In an underground mine, the average discrepancies between Smart Compass-Clinometer and the conventional compass-clinometer were2.57°in dip and 4.57° in dip direction.Smart Compass-Clinometeroffers geoscientists afast, reliable, and convenient tool

forgeological investigation.

**Keywords:**Smart Compass-Clinometer; smartphone application; geological site investigation; compass-clinometer; stereographic projection; instability analysis

## 1. Introduction

The rapid uptake of smartphones has led to a variety of smartphone applications and mobile technologies. Smartphonesoffer increased mobility and connectivity in comparison with desktop or laptop devices. These advantages enable the development of a wide range of software to assist users, which can utilizedata from built-in sensors including cameras, microphones, and accelerometers. Built-in accelerometers and magnetometersareuseful for measuring gravity and geomagnetic fieldsquickly, techniques which are useful for field investigationsthat require a large number of measurements.

Geological site investigation requires integrated processes from data acquisition to analysis. Rapiddata acquisition is often required for immediate decision making in applications such as underground mining and tunnel construction. Conventional geological site investigation includes measurement usingcompass-clinometers, transferof the measured data to a device such as a desktop or a laptop computer, and analysis of the data using specific software. This process requires exclusive devices for each step.Furthermore, the precision and accuracy of data depend on the skill level of the operator. Some time-consuming steps and processes that introduce inaccuracies can be improved by devices such asdigital compass-clinometers.However,these devices are expensive and consequently are rarely used (Lee et al., 2012a).

Several studies have examined geological applicationsfor smartphones. One of the most recent examples discusses theGeoTools software(Weng et al.,2012). GeoTools is anandroid-based smartphone applicationemploying several of the capabilities of smartphonesfor supporting measurements of geological structures, photography, and note-taking. Other studies have recommended similar smartphone-based applicationsfor field investigations, but these studies focused on measurement and recording utilities, and did not consider visualization or analysis of measured data (McCarthy et al., 2009; Roh et al., 2010). Overall, the majority of smartphone applications currently available for geological investigation onlymeasurethe orientation of planar structures, and provide very simple data visualization (Table 1). In a geological survey with many investigators, data acquired by multiple smartphone devices should be combined rapidly using their wireless transferring capability. Also, the obtained data should be analyzed on the device to acquire useful information quickly on the field survey for the rapid decision making. Neither the research applications nor the commercial applications have not considered this prospect, so they require additional processes and functionalities to acquire further information using the data. They are therefore not suitable for geological site investigations, due to the lack of analytical utilitiesthat organize field data.

Table 1. List of smartphone applications for geological field surveys.

| Name | Developer | Platform | Main functions |
|---|---|---|---|
| Clinometer Compass | Yu Saito | iOS | Measures orientations |
| Geology Compass | Pusch Ridge Consulting | iOS | |
| GeolCompass | Tecton Software, Inc. | iOS | |
| GeoStrike | Tectonic Engineering Consultants Co. Ltd. | iOS | |
| ezClinometer | Sora Takayama | Android | |
| GeoCompass | Luca Innocenti | Android | |
| Geological Compass | THSoft Co., Ltd. | Android | |
| GeoTools[a] | Weng et al.(2012) | Android | |
| Simple Geological Clinometer | Teraz | Android | |
| Field Compass | Aaron Averett | iOS | Measures orientations andplots the data on a map |
| GeoAttitude | Tectonic Engineering Consultants Co. Ltd. | iOS | |
| GeoClino for iPhone | Geological site investigation of Japan, AIST | iOS | |
| Geologist's Compass | Lemon Studio | iOS | |
| eGeo Compass | GeoStru Software | Android | |
| Strike and Dip | Major Forms | Android | |
| ListerCompass | The Virtual Explorer Pty., Ltd. | iOS | Measures orientations andplots the data on a stereonet |
| GeoClino for Android | GSI Co., Ltd. | Android | |
| Lambert | Pusch Ridge Consulting | iOS | Measures orientations andplots the data on mapand stereonet |
| Rock Compass | Parteq Innovations | iOS | |
| Rocklogger | RockGecko | Android | |

[a]Application for research (not commercially available)



This research presents aniPhone-based applicationfor geological site investigations. It also introducesSmart Compass-Clinometer,which is able to combinevarioussurveying techniques. Smart Compass-Clinometer includes a digital compass-clinometer, a visualization module that produces stereographic projections, a slope instability analysis module, and a data management module. We developed an algorithm for measuring strike and dip using sensor data, and compared the accuracy and precision to values obtained from a conventional compass-clinometer. Thisstudydescribes the concepts and details of the development of Smart Compass-Clinometer.

## 2. Background theory

The principlesand processesof data acquisition, visualization, and analysis using Smart Compass-Clinometer are described in the following sections.

### 2.1. Acquisition of strike and dip data

When measuring geological structures, the orientation of the smartphone is considered as the orientation of the structure. The built-in accelerometer and magnetometer in smartphoneshave a three-dimensional coordinate systemwithits center at (0, 0, 0). The axes parallel to the screen of the smartphone are the X and Y axes, and the axis normal to the screen is the Zaxis. Acceleration and geomagnetic fieldstrength acquired from the sensors provide values relative to the state of the smartphone. The accelerometer provides the acceleration due to gravity in g-force,and the magnetometer provides the strength of the geomagnetic field in microtesla (μT). As other electronic components in smartphones interfere with the magnetometer, smartphone operating systems provide a calibrated value to eliminate this. Accordingly, we have not added additional calibration in the application.The direction of gravity and the geomagnetic field are required to calculate the orientation of the smartphone. Additionally, when taking measurements, the smartphone must be stable to obtain an accurate value for acceleration due to gravity.

The angle of dip is equivalent to the angle between the vector normal to the smartphone screen and the vector normal to the horizontal plane. In the coordinate system of the smartphone, the vector normal to the screen is equal to N(0, 0, ±1), and the vector normal to the horizontal plane is equal to the acceleration vector G($G_x$, $G_y$, $G_z$), which is obtained from the accelerometer(Fig. 1). The angle of dip, d(radians), can be calculated using these vectors as detailed in Eq. (1).

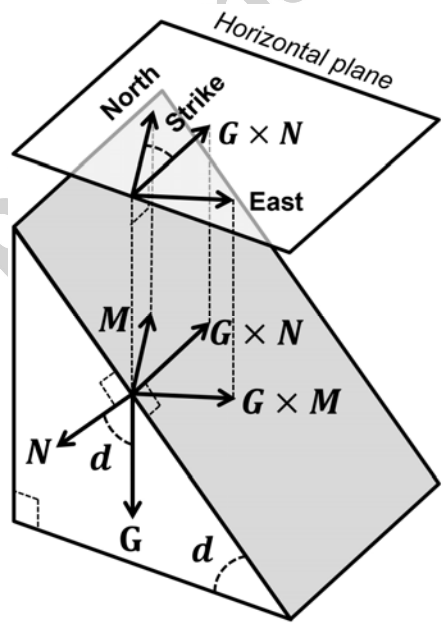


Fig. 1. Components required for calculating smartphoneorientation.

$$d(dip\ angle) = cos^{-1}\left|\frac{G_z}{|G|}\right| \tag{1}$$

The cross product of these vectors, G×N, is parallel to the smartphone screen andnormal to the direction of gravity, thus equal to the strike of the screen. The direction of the strike vector G×N is calculated using the magnetic field vector, M. However, the direction of the strike vector is not equal to the angle between the strike and magnetic field vectors,asthe geomagnetic field of the Earth is usually not parallel to the surface. The strike can be precisely calculated by using a cross product of G and M, which results ina vector directed east(90°) al plane. Based on these relationships, the angle of dip and the strike can be calculated, and strike can be converted to the dip direction according to the preferences of the user.

The algorithm for measuring a lineation is almost identical to that used for planar surfaces, but theorientation usually differs from the planar structure bearing the lineation. Smartphone have one long side (Y-axis), which can be used for measurement by placing it along the lineation. In this case, theplunge of the lineation is calculatedusingEq. (2).

$$p = sin^{-1}\left|\frac{G_y}{|G|}\right| \tag{2}$$

2.2. Use of stereographic projection visualizations

Stereographic projectionsare generally used for visualization of three-dimensional data in two-dimensional space, and are particularly usefulfor representing geological structures. These projections are also used in various other scientific fields, and an algorithm for creating them has been developed previously (Lisle and Leyshon, 2004). The visualization module of Smart Compass-Clinometer includes both equal-angle and equal-area equatorial nets. A rose diagram utility is also included which can rapidly producea visualization of directional information fromthe measured data.

2.3. Instability analysis of jointed rockmassesusing smartphones

The presence of unfavorably oriented discontinuities is a major cause of slope failures (Admassu and Shakoor, 2013).Instability analysis using stereographic projectionsallows instantrisk analysis of target rock slopes.Based on information regarding the joint structure, angle of friction, slope direction, and slope angle, both potentially unstable blocks of rock on the slope and the type of instability can be identified using this technique (Wyllie and Mah, 2004).Smart Compass-Clinometer includes planar, wedge, and toppling failure analysis,which are common applicationsfor instability analysis (Wyllie and Mah, 2004).Each failure analysis is based on Markland's test (Hoek and Bray, 1981) for identifying significant discontinuities on stereonet. Figure 2 shows the failure modes and its representation on stereonets. A Plane or a wedge failure takes place when the dip of the sliding plane or the plunge of the line of intersection is less than the dip of the slope face(Wyllie and Mah, 2004). A toppling failure occurs when the dip direction of the discontinuities dipping into the face is within about 10° of the dip direction of the face (Wyllie and Mah, 2004).Applying these theories, Smart Compass-Clinometer produces text reports which containspotentially unstable structures in current dataset. The structures are also highlighted on stereonet for providing visual data representation.

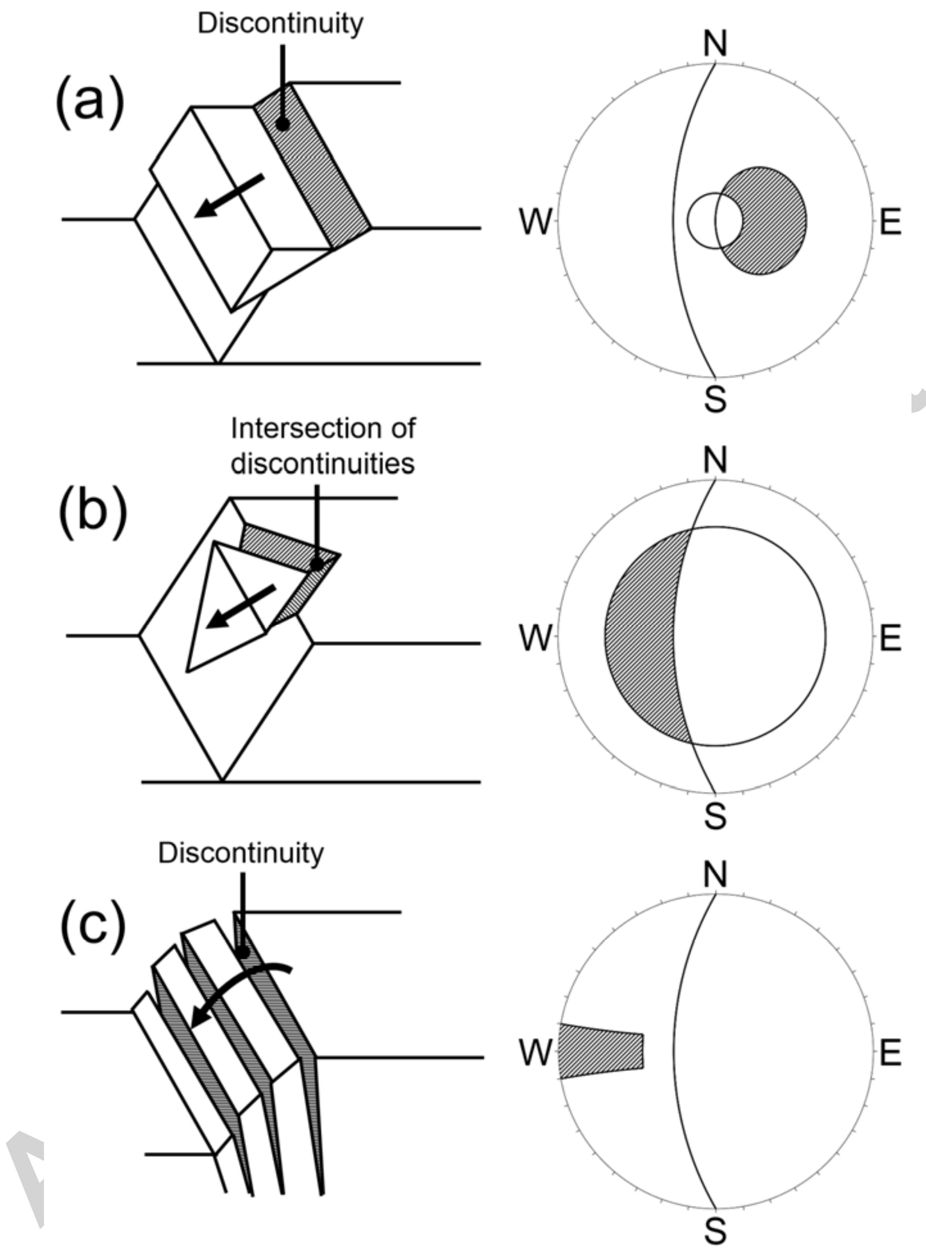


Fig. 2. Representative failure modes and their representation on stereonets. Grey area on stereonets are envelopes which indicates structures inside them are unstable. (a) Plane failure. (b) Wedge failure. (c) Toppling failure (modified after Hoek and Bray, 1981).

## 3. Development of a smartphone-based geological site investigationapplication

Smart Compass-Clinometer consists of the digital compass-clinometermodule for measuring the orientation of geological structures, avisualization module for plotting data on stereographic projections, a data analysis module for instability analysis, and a data management module for sharing and exporting data(Fig. 3). A single common database is used by all modules for recording and accessing data. Calculation of the orientation of structures is provided by the compass-clinometer module, and the data can then be used by other modules for real-time analysis.Development of the application was conducted using an iPhone 4 device, which has an accelerometer, a magnetometer and a GNSS (Global Navigation Satellite System) receiver.

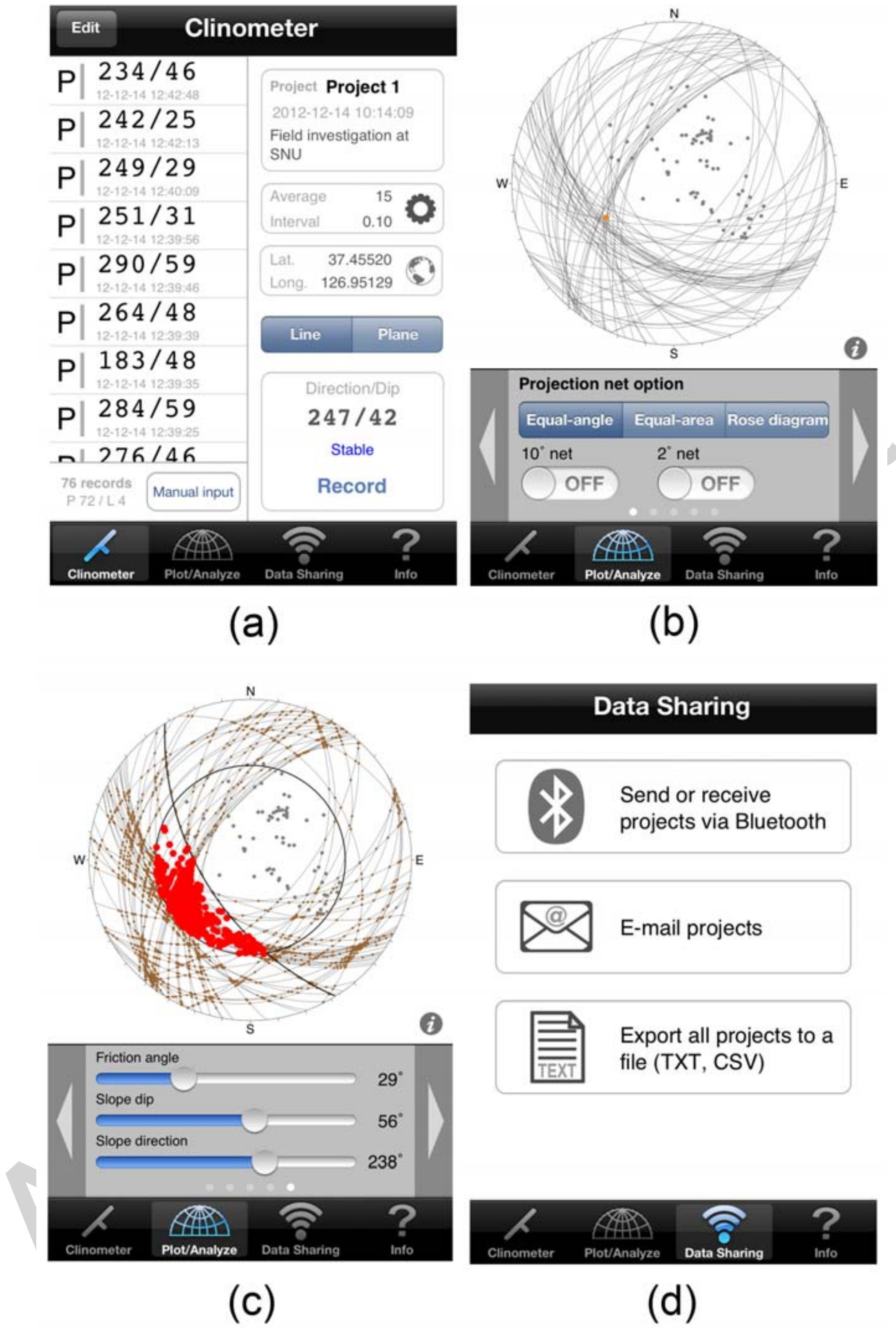


Fig. 3. Components of Smart Compass-Clinometer. (a) Clinometer module.(b) Data visualization module. (c) Data analysis module.(d) Data management module.

3.1. Clinometer module

The compass-clinometer module measures the orientation of geological structures using built-in sensors. Currently, this process is performed using aconventional analog compass-clinometerwith one edge placed against thestructure. Conventional compass-clinometers must be held horizontal and stable before a reading is taken.An additional process is then required to acquire the angle of dip.This can be a particularly time-consuming and arduous task in the field.The algorithm described previouslywas developed to allow almost instant measurement of strike and dip without the requirement for calibration in a horizontal position. Smart Compass-Clinometerusers can measure a structure easily and promptly by placing the smartphone on the structure in any direction and tapping the measurementbutton. The measured data are compiled into a dataset, which can then be used foranalysis or shared over wireless connections.

The orientation of the smartphone is calculated at 0.1s intervals. To eliminate the effect of small-scale fluctuations, up to100measurements are averaged to calculate the orientation of the phone.We found that the precision of orientation data improvedwith increasing number of measurements considered in the average value(Lee et al., 2011). However, this also increases the time required to complete measurement in the field. We therefore developed an option for users to adjust the number of measurements included in the averaged value(Fig. 4a). The variance of measurements is also calculated, allowing the application to notify users of the level of instability affecting the measured data, anddeliver warnings where large errorsare introduced as a result of magnetic interference or instability.A short sound emanateswhen the user records the current orientation, and a different sound is activatedif the variance exceeds a threshold level(e.g., 2°in the angle of dip or 5°in the dip direction).Users are therefore notified of significant errors without having to check the screen. During field investigations, users can also add a photo of the target, a text note describing the structure, anda geographical coordinate acquired by the GNSS receiver. Thiscoordinate data can then be plotted on the iPhone's built-in mapping application(Fig. 4b).

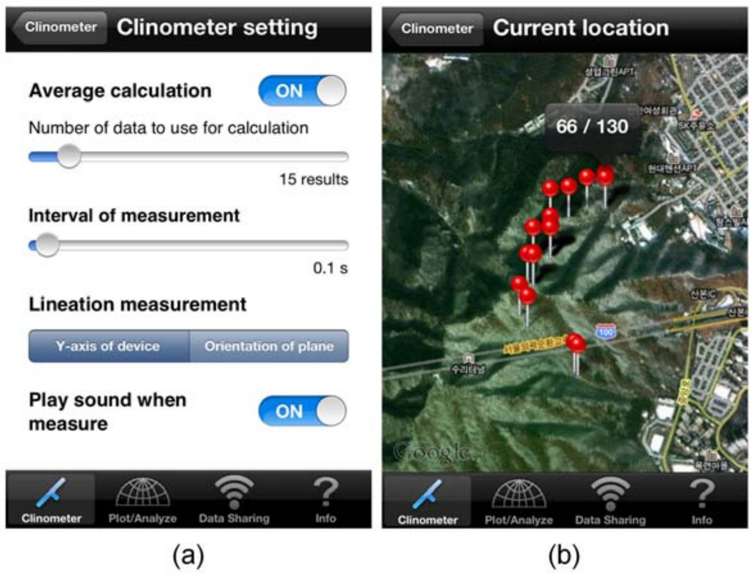


Fig. 4. User interfaces of the compass-clinometer module. (a) Clinometer settings.(b) Map displaying coordinate data.

## 3.2. Data visualization module

The visualization module can produce various stereographic projection images on the smartphone screen. Legibility of these images is a particular concern given the small sizes of most screens. Projection nets generally have grid lines at 2°intervals from 0 to 90°, but these are not essential while working on small screens. Therefore, options for selecting the interval between gridlines were added to the application. The grid lines are plotted on the device using mathematical formulae to ensure a precise result.

Measurement data from Smart Compass-Clinometer can describe planar and linear geological structures.Planar structure data are plotted as apole on the stereographic projection, which represents a lineation normal to the planar structure. The visualization module draws the intersection of these structures with the planar structure, and includes options for plotting specific types of structures or intersections(Fig. 5).The current orientation of the smartphone also can be plotted on the stereographic projection net while conducting surveys or analyzing data.

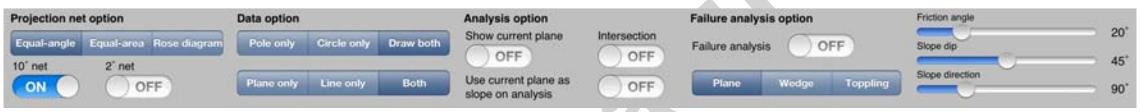


Fig. 5. User interface for selecting options in the visualization and analysis module.

3.3. Data analysis module

The analysis module automatically performs instability analysis using standard techniques on aselected dataset. This module is combined with the visualization model to plotthe resultsona stereographic projection. If further information is required for data analysis, such as the intersections of planar structures, the module calculates it automatically and plots the results (Fig. 6a). The analysis utility performs instability analysis for three types of slope failures (plane failure, wedge failure, and toppling).Specific structures which my induce failure are identified first.Thesestructures are then highlighted on the stereographic projection,and a results screen providesstatistics to enable users to quickly identify areas of interest (Fig. 6b). All the results from the instability analysis can be exportedas a text file for further use.The combined features of the visualization and analysis modules provide real-time visualization of geological structures during data collection, providing an intuitive understanding of the field site.

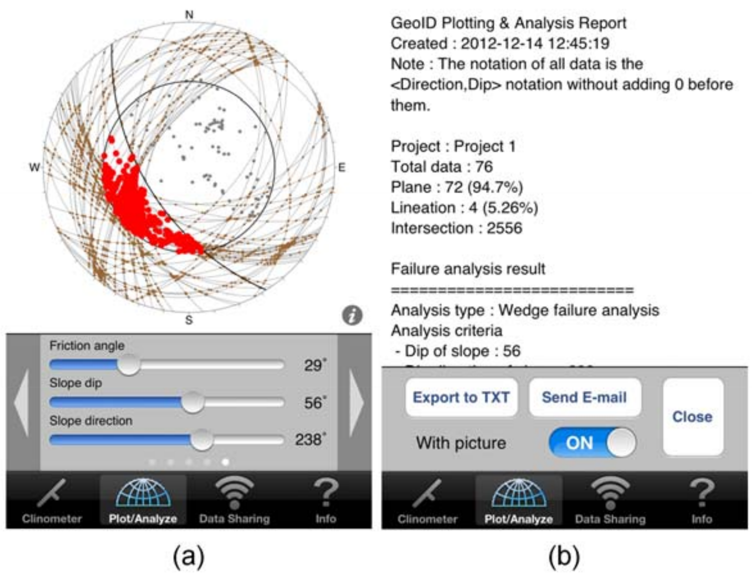


Fig. 6. Example of results from slope instability analysis performed using Smart Compass-Clinometer. (a) Analysis screen. (b) Detailed statistical results screen.

## 3.4. Data management module

The data management module consists of the database module, a wireless data sharing utility, and a data export utility. Smart Compass-Clinometer uses the SQLite database management system, which is included in mostmobile operating systems. In theory, a single SQLite database file can contain more than twobillion measurement recordsfromSmart Compass-Clinometer, as long as those records do not contain text notesor photographs.

Figure7shows thedata flow inSmart Compass-Clinometerfrom the acquisition of sensor data to the export of the database. Orientation data acquired using the compass-clinometer module arerecorded by the data management module using SQLite3. The data management module also provides specific data required for various operations in other modules.

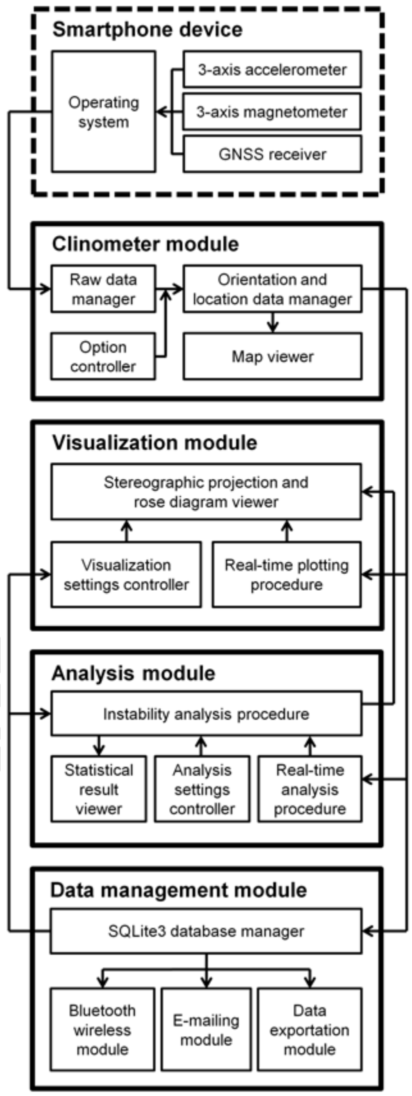


Fig. 7. Data flow inSmart Compass-Clinometer.

The wireless data sharing utility sends and receives databetween two or more users via Bluetooth, a standard technology for exchanging data over short distances. It does notrequire a connection to a cellular network,such as 3G or 4G,to transfer data(Fig. 8). Thisutility is essential toSmart Compass-Clinometer,as geological site investigationsareoften conducted in areas outsidethe range of cellular networks (e.g.,deep underground or in remote areas), and users need to combine measured data for rapidanalysis in the field.

The export utility can be used transfer the entire database in a text file and analyze it with other software. There are several options available when completing exports, such as data format and notation used, to suit the needs of users.


Fig. 8. Wireless data transfer of datasets between two devices using Bluetooth.(a) Screenshot from the sending device. (b) Screenshot from the receiving device.

## 4. Applications and validations of Smart Compass-Clinometer

### 4.1. Precision of the digital compass-clinometer

We assessed the precision of data collectedby the compass-clinometer module using an iPhone 4 on which Smart Compass-Clinometerwas installed. We measured the angle and direction of dip in anindoor environmentfree from vibrationsand magnetic interference. We tested Smart Compass-Clinometer in 16 different orientations with 1000 measurementsin each orientation.

The maximum standard deviation in the angle of dip was 0.122° and the minimum was 0.096°. Overall, the standard deviation of the measurementsdepended on the orientation of the device. For the dip direction,the maximum standard deviation was 3.004° and the minimum was 0.849°. The maximum difference between the average and median measurements was 0.015°in theangle of dip angle and 0.130°inthe dip direction. The precision of measurements of the angle of dipwashigher than thoseof dip direction as the calculation of the dip direction requires additional sensor data.The precision in the measurements of the angle of dip was sufficient to detect differencesas low as 0.1°.Measurements of dip direction weresufficiently precise to distinguish differences as low as 0.5°.

Forgeological site investigations, the number of measurements collected for each measurement must be determined to balance precision and the time required for measurement.When we reduced the averaged measurement to five measurements,thestandard deviation in the angle of dip increased to a maximum of 3.34°, and the dip direction fluctuated within ±5.00°. We determined that 50 measurements is appropriate for an averaged measurement,which takes 2.5 s and results in a standard deviation less than 1.0°.

## 4.2. Accuracy of Smart Compass-Clinometer

Testswere conducted inboth outdoor and underground environments to assess the accuracy of the application in settings similar to those in which it will be commonly used.The outdoor testswere conducted on severalslopesaroundthe Seoul National University campus in Seoul, South Korea. In these tests, theorientations of 40structures were measured usingSmart Compass-Clinometer. The measured valueswere compared to thoseacquiredby an experienced investigator usinga conventionalcompass-clinometer(Table 2).The maximum precision of the conventional compass-clinometerwas assumed to be0.3°. To ensure consistency in the precision of the two instruments,10measurements were used for a single measurement taken usingSmart Compass-Clinometer(Lee et al., 2012b).

The average absolute differencein measured values between Smart Compass-Clinometer and the conventional compass-clinometer was 1.70° in the angle of dip and 2.63° in dip direction. Measurements of dip direction showed greater disparity due to high variability in the magnetometer.Correlation plots between the measured values using both devices are illustrated as figure 9(a) and figure 9(b). Outlierresults showeddisparities up to 7°between the two methods of measurement, but the majority of tests demonstrated that the two methods were relatively consistent. Figure 9(c) and figure 9(d) show differences between the two methods according to dip and dip direction of target structure. Correlation between dip angle and difference of measurements of the two methods was not found. Meanwhile, dip direction and the difference of the values show periodic correlation which might be caused by imperfect correction of the magnetic interferences.

Table 2. Orientations of geological structures measured with a smartphone and a conventionalcompass-clinometer in an outdoor environment.

| No. | Dip (degrees) | | | Dip direction (degrees) | | |
|---|---|---|---|---|---|---|
| | Smartphone | Clinometer | Difference | Smartphone | Clinometer | Difference |
| 1 | 47 | 48 | 1 | 330 | 328 | 2 |
| 2 | 26 | 27 | 1 | 118 | 121 | 3 |
| 3 | 38 | 38 | 0 | 237 | 241 | 4 |
| 4 | 54 | 55 | 1 | 245 | 247 | 2 |
| 5 | 42 | 49 | 7 | 194 | 193 | 1 |
| 6 | 47 | 48 | 1 | 221 | 225 | 4 |
| 7 | 51 | 53 | 2 | 40 | 39 | 1 |
| 8 | 64 | 67 | 3 | 115 | 112 | 3 |
| 9 | 9 | 14 | 5 | 340 | 334 | 6 |
| 10 | 42 | 44 | 2 | 181 | 180 | 1 |
| 11 | 39 | 41 | 2 | 162 | 167 | 5 |
| 12 | 12 | 13 | 1 | 287 | 287 | 0 |
| 13 | 56 | 58 | 2 | 238 | 244 | 6 |
| 14 | 36 | 36 | 0 | 147 | 154 | 7 |
| 15 | 7 | 8 | 1 | 109 | 109 | 0 |
| 16 | 36 | 43 | 7 | 214 | 217 | 3 |
| 17 | 57 | 58 | 1 | 154 | 152 | 2 |
| 18 | 68 | 69 | 1 | 47 | 43 | 4 |
| 19 | 31 | 31 | 0 | 149 | 149 | 0 |
| 20 | 65 | 65 | 0 | 8 | 5 | 3 |
| 21 | 23 | 23 | 0 | 146 | 144 | 2 |
| 22 | 12 | 13 | 1 | 129 | 128 | 1 |
| 23 | 34 | 36 | 2 | 54 | 50 | 4 |
| 24 | 58 | 59 | 1 | 123 | 125 | 2 |
| 25 | 66 | 66 | 0 | 206 | 208 | 2 |
| 26 | 19 | 20 | 1 | 213 | 215 | 2 |
| 27 | 75 | 73 | 2 | 30 | 33 | 3 |
| 28 | 63 | 65 | 2 | 195 | 194 | 1 |
| 29 | 71 | 72 | 1 | 341 | 342 | 1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 30 | 46 | 47 | 1 | 182 | 181 | 1 |
| 31 | 31 | 32 | 1 | 139 | 137 | 2 |
| 32 | 88 | 90 | 2 | 234 | 234 | 0 |
| 33 | 27 | 28 | 1 | 302 | 299 | 3 |
| 34 | 64 | 66 | 2 | 200 | 205 | 5 |
| 35 | 18 | 22 | 4 | 265 | 269 | 4 |
| 36 | 61 | 61 | 0 | 200 | 205 | 5 |
| 37 | 71 | 72 | 1 | 35 | 37 | 2 |
| 38 | 67 | 68 | 1 | 167 | 167 | 0 |
| 39 | 61 | 63 | 2 | 242 | 249 | 7 |
| 40 | 74 | 79 | 5 | 208 | 209 | 1 |
| | Average | | 1.70 | Average | | 2.63 |
| | Standard deviation | | 1.71 | Standard deviation | | 1.93 |

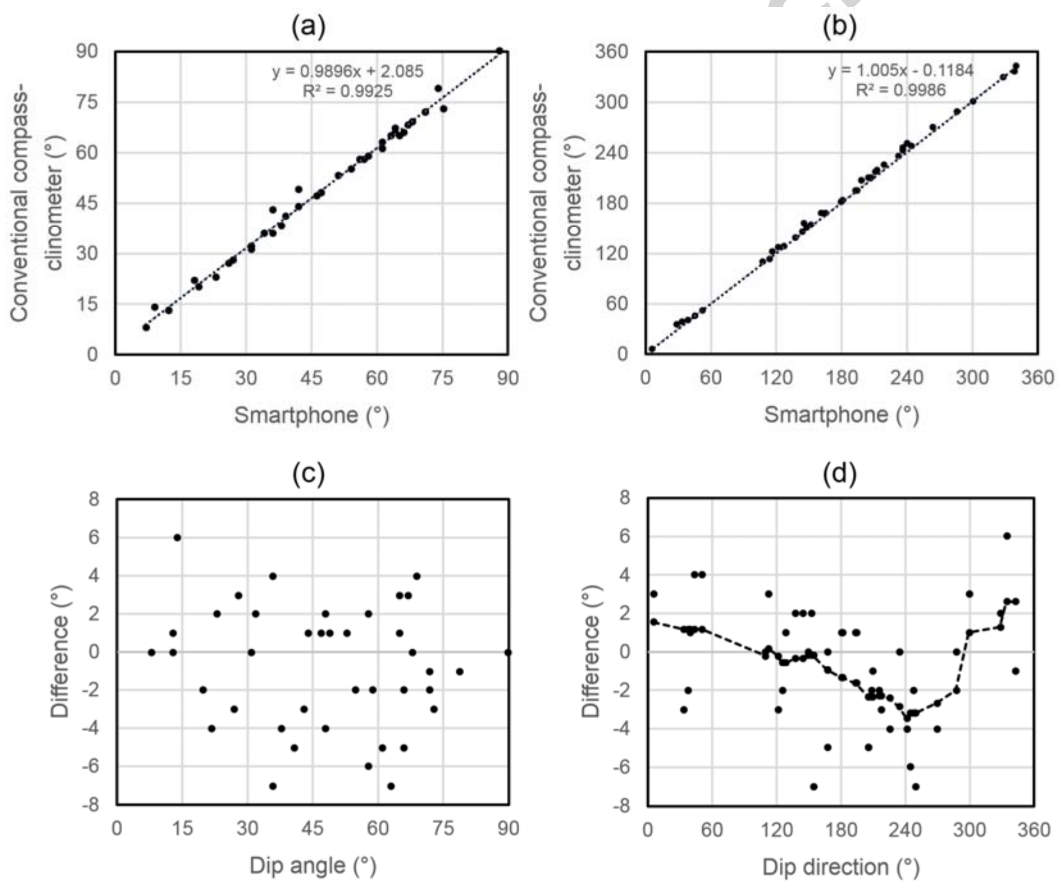


Fig. 9. Plots showing correlations between (a) dip angle measured with Smart Compass-Clinometer and conventional compass-clinometer, (b) dip direction measured with the two

types of devices, (c) dip angle and the difference of values measured with the two types of devices, and (d) dip direction and the difference of the values.

We conducted underground testing in a mine passage located in Samcheok City, Gangwon-do, South Korea. We took measurements at 21 points within the mine passage,more than 50m below the entrance of the mine.The methods and parameters we used were consistent with the outdoor tests(Table 3). In the underground mine, the average differencebetween valuesmeasured by Smart Compass-Clinometer and the conventionalcompass-clinometer was 2.57° in dip and 4.57° in dip direction. The disparity between measurement techniques in most cases was similar to those observed in the outdoor tests. Consequently, the outlier disparities are assumed to be a result of error introduced by magnetic interference from themine infrastructure or by the roughness of the rock surface.Smart Compass-Clinometer generally worked well without cellular or Wi-Fi network connections, asidefrom utilities such as email that rely on these networks. The lack of network connectivity did not appear to affect themeasured valuesin any way.



Table 3. Orientations of geological structures measured with a smartphone and a conventional compass-clinometerin an underground environment.

| No. | Dip (degrees) | | | Dip direction (degrees) | | |
|---|---|---|---|---|---|---|
| | Smartphone | Clinometer | Difference | Smartphone | Clinometer | Difference |
| 1 | 71 | 71 | 0 | 183 | 183 | 0 |
| 2 | 80 | 80 | 0 | 189 | 187 | 2 |
| 3 | 86 | 88 | 2 | 252 | 248 | 4 |
| 4 | 81 | 88 | 7 | 13 | 8 | 5 |
| 5 | 84 | 80 | 4 | 172 | 175 | 3 |
| 6 | 71 | 67 | 4 | 247 | 240 | 7 |
| 7 | 80 | 70 | 10 | 190 | 183 | 7 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 8 | 67 | 70 | 3 | 9 | 7 | 2 |
| 9 | 81 | 85 | 4 | 179 | 165 | 14 |
| 10 | 67 | 70 | 3 | 189 | 192 | 3 |
| 11 | 79 | 80 | 1 | 108 | 106 | 2 |
| 12 | 28 | 30 | 2 | 348 | 333 | 15 |
| 13 | 88 | 89 | 1 | 206 | 204 | 2 |
| 14 | 89 | 90 | 1 | 268 | 268 | 0 |
| 15 | 65 | 65 | 0 | 40 | 45 | 5 |
| 16 | 86 | 84 | 2 | 184 | 189 | 5 |
| 17 | 75 | 67 | 8 | 51 | 55 | 4 |
| 18 | 78 | 77 | 1 | 281 | 289 | 8 |
| 19 | 89 | 89 | 0 | 75 | 75 | 0 |
| 20 | 89 | 90 | 1 | 237 | 231 | 6 |
| 21 | 88 | 89 | 1 | 235 | 229 | 6 |
| 22 | 88 | 89 | 1 | 42 | 38 | 4 |
| 23 | 74 | 77 | 3 | 49 | 50 | 1 |
| | Average | | 2.57 | Average | | 4.57 |
| | Standard deviation | | 2.66 | Standard deviation | | 3.89 |

Theoretically, the orientation of the rock structure provided by Smart Compass-Clinometershould remain fixed while rotating the smartphone on a planar structure.However, we observed variations of up to 7.5° while rotating the smartphone on a plane. This may be one of the factors explaining the disparity between Smart Compass-Clinometer and the conventional compass-clinometer, and is likely to be the result of incomplete correction of internal magnetic interference. We completed a manual compensation for this by rotating the device so that the operating system measured the strength and direction of the magnetic interference.After compensating for the interference, the variation in the measured value decreased to1°.The magnetic interference is largely attributable to other chipsets adjacent to the magnetometer. The correction of the interference was assumed to be ideal, but the correction algorithm requires the user to physically move the device. The problem of magnetic interference can be resolved by attaching an external measuring device which is not affected by internal magnetic field generated by other smartphone components. It could also be resolvedby adding an additional compensation step in the measurement process, but this will increase the time required to take each measurement.

### 4.3. Applicationof Smart Compass-Clinometer to evaluate slope instability

We selected the rock slopes of Ulleung-Do as a study area to apply Smart Compass-Clinometer for slope instability analysis. Ulleung-Do is an island in the East Sea, Korea, locatedapproximately 130km east off the KoreanPeninsula(37°30′N, 130°52′E). The island has an area ofapproximately 72 $km^2$(11.3 km in length and 12.4 km in width)and supports approximately 10,830 inhabitants. It is volcanic in origin, consisting primarily of trachyandesite rock.The rocky, steep-sided island is the top of a large stratovolcano, which hasrisen from the seafloor and reached a maximum elevation of 984 meters above sea level.Most of rock slopes around the coastal road are very steep (>55° inclination), and areweathered from the exposure to seawater.

Two experienced investigators conducted a geological assessment of the study site. Using Smart Compass-Clinometer, they acquired data from 16 different discontinuous rock slopes, primarily located along the coastal road in Ulleung-Do (Fig. 10). The orientation of the slopes and several representative rock mass joints were measured to analyzethe risk of slope failure. They also determined the average block size and joint spacing of the rock mass. Furthermore, rock hardness was measured using a Schmidt hammer and converted to the uniaxial compression strength (UCS). The measured dataset and accompanyingdescriptions of each slope were stored and managed using Smart Compass-Clinometer.

The stability of rock slopes was assessed by examining the risk ofthree types of failure (plane failure, wedge failure, and toppling) using stereographic projections. For each slope, the density of the rock mass was assumed to be 30kN/$m^3$. Figure11provides an example ofimages captured and stored using Smart Compass-Clinometer, andthe results of theslope stability analysis. Points in black indicate thepole of a planar discontinuity in therock mass, and red pointsindicate those poles that are located within a potential failure zone. The complete results of the slope stability analysis are detailed in Table 4. It was found that six of the 16sites are vulnerable to plane failure, and 9 sites arevulnerable to wedge failure.

Using Smart Compass-Clinometer, it took approximately12 minutes to complete theslope instability assessment at each site, including data acquisition, visualization, analysis, and photography.Without travel time, approximately 3 hours wererequired to obtain, record, visualize, analyze, and photograph orientation data from 173geological structuresover16 sites.Most of the time was consumed for selection of proper structure to measure. Time required for all the measurements was less than 10 percent of total investigation process since less than 2 seconds is required to measure each structure using Smart Compass-Clinometer. A person with 5 years of experience with a conventional compass-clinometer took 35 seconds on average to measure a structure using the conventional tool. Therefore, the total investigation time would be extended more than 53% (95 minutes) if the investigation was performed using the conventional tools, without considering other processes such as data recording.

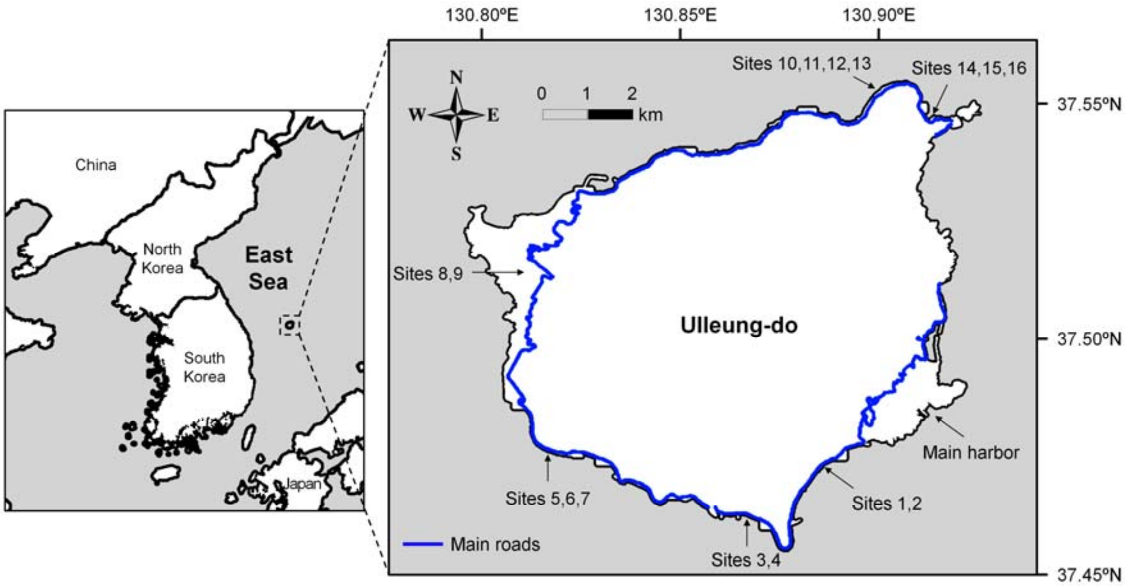


Fig. 10. Map of Ulleung-Do showing the 16 rock slopesitesanalyzed, and the main roads.

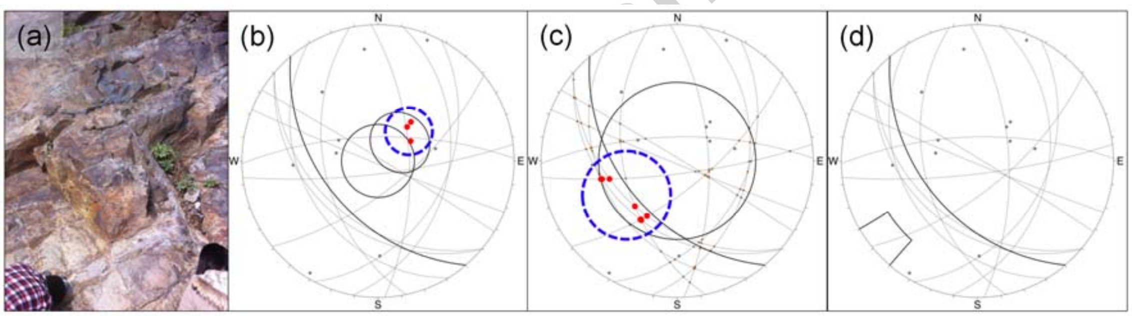


Fig. 11. Results of the rock slope stability analysis from Site No. 2 on Ulleung-Do. (a) Photographof the rock slope taken and stored with Smart Compass-Clinometer. (b) Stereographic projection showing the plane failure analysis. (c) Stereographic projection showing the wedge failure analysis. (d) Stereographic projection showing the toppling failure analysis.

Table 4. Stability analysis ofdiscontinuous rock slopes in Ulleung-Do, South Korea.

| Site No. | Geographical coordinate | | Rock slope failure type[a] | |
|---|---|---|---|---|
| | Latitude | Longitude | Plane failure | Wedge failure |
| 1 | 37.4710 | 130.8850 | | |
| 2 | 37.4712 | 130.8850 | √ | √ |
| 3 | 37.4603 | 130.8650 | | |
| 4 | 37.4603 | 130.8650 | √ | √ |
| 5 | 37.4736 | 130.8140 | √ | √ |
| 6 | 37.4737 | 130.8140 | | √ |
| 7 | 37.4736 | 130.8140 | √ | |
| 8 | 37.5103 | 130.8080 | | |
| 9 | 37.5136 | 130.7970 | | √ |
| 10 | 37.5465 | 130.8980 | √ | √ |
| 11 | 37.5460 | 130.8970 | | √ |
| 12 | 37.5464 | 130.8980 | | |
| 13 | 37.5459 | 130.8970 | √ | √ |
| 14 | 37.5411 | 130.9120 | | |
| 15 | 37.5415 | 130.9130 | | |
| 16 | 37.5413 | 130.9120 | | √ |

[a] Toppling failure is not detected at all sites



## 5. Conclusions

Smart Compass-Clinometer enables rapid, accurate measurement for geological site investigations, and on-sitestability analysis for a variety of geoscience fields. It is easily accessible given that is makes useof popular devices, thus reducing the time and costs involved withgeological site investigation. The analysis tool embedded in the software can perform data analysis immediately following data collection, and does not require additional steps for importing or exporting measured data. Data can be visualized concurrently with data analysis using stereographic projections, aiding intuitive understanding of the study site. Data can also be exported using the data management module, maximizing the applicability of Smart Compass-Clinometer to geoscience investigations.Our case studyin Ulleung-Do demonstrated thateffective geological investigationcan be completed over a widespread area in a few hours with Smart Compass-Clinometer.This is significantly faster than is possible with conventional instrumentation such as compass-clinometers, cameras, and GPS devices.

By integrating existing techniques, Smart Compass-Clinometer can provide convenient and useful functions required for geological field investigation from measurement of structures to analysis and management of the data. It is not just a collection of tools but a systematic combination of several tools to aid information acquisition and decision making on the field thatprevious research or software did not consider.

Whenconducting a large field survey project over a wide area, a server may be required forcombining all the data collected, rather than attempting to use the Bluetooth. As the Bluetooth protocol only supports short-distance connections, it may not be appropriate in applications that require large amounts of data collected over a wide area.

The rapid development of smartphone technology is providing new solutions in various scientific fields. Smart Compass-Clinometer illustrates some of the possibilities of such technology. With more precise sensors, compensation algorithms, and improved processing speed, the capability of Smart Compass-Clinometer can be extended further as the capabilities of smartphones increase in the future.

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**Captions**

Fig. 1. Components required for calculating smartphone orientation.

Fig. 2. Representative failure modes and their representation on stereonets. Grey area on stereonets are envelopes which indicates structures inside them are unstable. (a) Plane failure. (b) Wedge failure. (c) Toppling failure (modified after Hoek and Bray, 1981).

Fig. 3. Components of Smart Compass-Clinometer. (a) Clinometer module. (b) Data visualization module. (c) Data analysis module. (d) Data management module.

Fig. 4. User interfaces of the compass-clinometer module. (a) Clinometer settings. (b) Map displaying coordinate data.

Fig. 5. User interface for selecting options in the visualization and analysis module.

Fig. 6. Example of results from slope instability analysis performed using Smart Compass-Clinometer. (a) Analysis screen. (b) Detailed statistical results screen.

Fig. 7. Data flow in Smart Compass-Clinometer.

Fig. 8. Wireless data transfer of datasets between two devices using Bluetooth. (a) Screenshot from the sending device. (b) Screenshot from the receiving device.

Fig. 9. Plots showing correlations between (a) dip angle measured with Smart Compass-Clinometer and conventional compass-clinometer, (b) dip direction measured with the two types of devices, (c) dip angle and the difference of values measured with the two types of devices, and (d) dip direction and the difference of the values.

Fig. 10. Map of Ulleung-Do showing the 16 rock slope sites analyzed, and the main roads.

Fig. 11. Results of the rock slope stability analysis from Site No. 2 on Ulleung-Do. (a) Photograph of the rock slope taken and stored with Smart Compass-Clinometer. (b)

Stereographic projection showing the plane failure analysis. (c) Stereographic projection showing the wedge failure analysis. (d) Stereographic projection showing the toppling failure analysis.

Table 1. List of smartphone applications for geological field surveys.

Table 2. Orientations of geological structures measured with a smartphone and a conventional compass-clinometer in an outdoor environment.

Table 3. Orientations of geological structures measured with a smartphone and a conventional compass-clinometer in an underground environment.

Table 4. Stability analysis of discontinuous rock slopes in Ulleung-Do, South Korea.

Computers & Geosciences

Smart Compass-Clinometer: a smartphone application for easy and rapid geological site investigation

Research highlights

- A geological smartphone application for measurement, visualization and analysis
- Algorithms for measuring orientations using built-in sensors
- Software structure and elementsfor geological site investigation using smartphone
- Validation of its precision and accuracy on actual devices
- Case study of slope instability analysisat Ulleung-Island using the application