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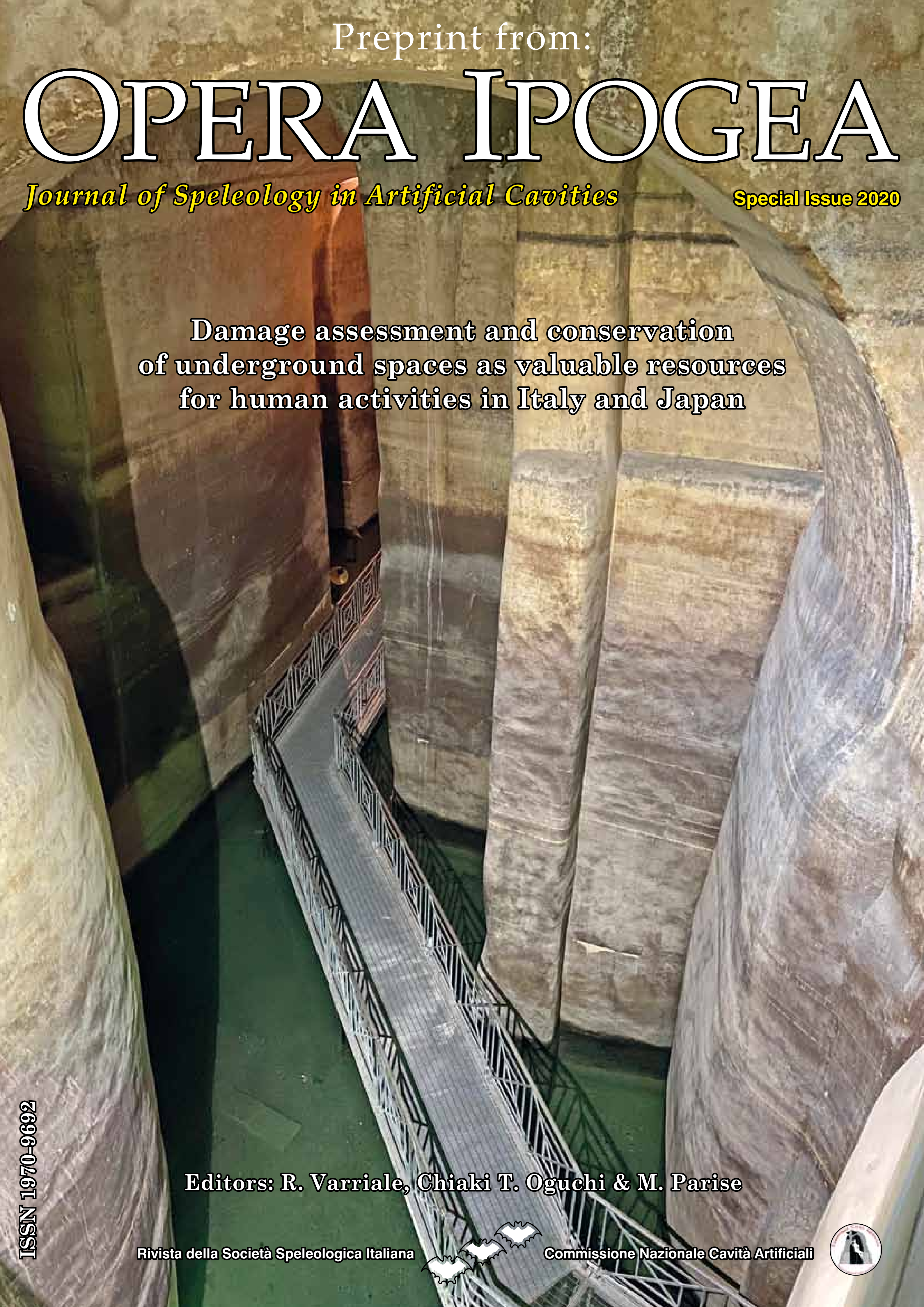

Damage assessment and conservation of underground spaces as valuable resources for human activities in Italy and Japan

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Dragon
Phoenix
Sanskrit characters mandala
18 disciples of the Buddha

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Three-dimensional point cloud data by terrestrial Laser Scanning for conservation of an artificial cave

Nuvole di punti tri-dimensionali da Laser Scanner terrestri per la conservazione di una cavità artificiale

Yuichi S. Hayakawa[1, 2], Takuro Ogura[3], Yasuhiko Tamura[2, 4], Chiaki T. Oguchi[5], Kisara Shimizu[5]

Abstract

Due to its invisibility and insufficient awareness in a local society, an underground building heritage (UBH) often suffers from degradation and destruction, and its conservation can be an urgent issue. Recent developments in the acquisition of high-definition topographic data enable us to acquire detailed three-dimensional morphological data of a cave as point cloud data and 3D mesh data which are useful for visualization of UBHs. We perform terrestrial laser scanning of an UBH, an artificial cave named Taya Cave, as a part of conservation activities of the site. Taya Cave is a registered cultural heritage in Yokohama City, Kanagawa Prefecture in central Japan. The terrestrial laser scanning was performed from multiple scan positions throughout the cave, and the point clouds were registered using the feature-based iterated closest point algorithm. The registered point clouds were then converted into a mesh model, to which face error corrections and a solid filling were applied. After these processes, the mesh model is printed out in three dimensions. The 3D print model of the cave is used for the class teaching in an elementary school in the local area, and such the visualization of the cave successfully enhanced the students recognition of the UBH. Effective and sustainable protection of the cave will further be possible by integrating geotechnical assessments and outreach activities in the local society.

Keywords: point cloud, terrestrial laser scanning, 3D print, outreach.

Riassunto

A causa della sua non visibilità e di insufficiente consapevolezza nella locale comunità, un elemento di patrimonio ipogeo (underground building heritage, UBH) può spesso soffrire per degrado e danni, tanto che la sua conservazione può divenire una questione di estrema urgenza. Recenti sviluppi nella acquisizione di dati topografici ad alta definizione consentono di acquisire dati tridimensionali morfologici di una cavità come nuvola di punti e griglia 3D che sono utili per la visualizzazione di UBH. Nel presente contributo si presentano i dati relative ad un rilievo laser scanner terrestre di una UBH, e precisamente di una cavità artificiale nominata Taya Cave, come parte delle attività di conservazione del sito. Taya Cave è un elemento del patrimonio culturale registrato nella città di Yokohama, nella Prefettura di Kanagawa nel Giappone centrale. Questa cavità artificiale è stata scavata per motivi religiosi, presumibilmente nell'ottavo secolo. Essa presenta una forma complessa, con un percorso stretto e sinuoso che si sviluppa su tre livelli. Alcuni settori della cavità presentano elementi di instabilità, anche con parti che sono già state interessate da crolli nel passato.

Il rilievo mediante laser scanner terrestre è stato eseguito da multiple posizioni di scansione all'interno della cavità, per il suo intero sviluppo, e le nuvole di punti così ottenute sono state registrate utilizzando iterazioni dell'algoritmo del punto più vicino, basato su elementi di riconoscimento. Le nuvole di punti registrate sono state poi convertite in un modello a griglia, al quale sono stati applicati correzioni degli errori e un riempimento solido. Dopo tali fasi di processamento, il modello a griglia è stato stampato in tre dimensioni. Il modello 3D della cavità artificiale è stato utilizzato per lezioni in una classe della locale scuola elementare, e la visualizzazione dell'ipogeo ha consentito con successo il riconoscimento della UBH da parte degli studenti. Una effettiva e sostenibile protezione della cavità potrà essere possibile mediante l'integrazione di analisi geologico-applicative e geotecniche per la valutazione della stabilità delle porzioni critiche all'interno dell'ipogeo, e per sviluppare azioni di educazione e divulgazione dei risultati dello studio nell'ambito della comunità locale.

Parole chiave: nuvola di punti, laser scanner terrestre, stampa 3D, campagna informativa.

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Introduction

An underground building heritage (UBH) can suffer from neglection and insufficient awareness in a local society because of its invisibility. Compared to more visual cultural heritages, including old buildings and monuments, degradation of UBHs is rather hard to be recognized, while its evaluation and damage assessment cannot be instantly performed by a manager or local owner, due partly to their complexity. In order to enhance the awareness of the cultural significance and degrading status of UBHs, it is necessary to visualize their shape and geographical context. Further, for the sustainable protection of UBHs, accurate safety assessment with geotechnical background, as well as their understandings among the local stakeholders would be required.

Recent developments in the acquisition and analysis method of high-definition (HD) topographic measurements enabled us to obtain detailed three-dimensional (3D) morphological data of a cave (e.g., Lerma *et al.*, 2010; Gallay *et al.*, 2016). Such 3D data can be utilized for visualization and structural analyses of cave morphology (Fabbri *et al.*, 2017). Laser scanning technology is one of the major approaches in measuring HD-topographic data in caves, because Laser scanning (or Lidar) enables to acquire highly-accurate spatial coordinates of target objects having a complicated 3D shape even in a dark and narrow spaces (Hayakawa & Oguchi, 2016).

The 3D point cloud showing the complex morphology of UBHs can be used to assess the current situation of the UBHs, including their morphological characteristics and the weathering conditions, and to perform stability analysis with engineering geological and geotechnical approaches. However, such use of point cloud is often insufficient to fully visualize and disseminate the characteristics of the UBH, particularly for the local community. It is necessary therefore to link the results of scientific measurement and stability assessment to the shared knowledge with the local people.

In this paper, we demonstrate the acquisition of 3D morphological data of an artificial cave as an UBH in Japan, whose complex 3D features have rarely been known so far. The obtained point cloud data are further utilized to disseminate the environmental and structural properties of the cave to the local people.

Study site

The study site is Taya Cave, located at Yokohama City in eastern Japan (fig. 1). This cave has been artificially excavated for religious purposes, presumably since the 8th century. It has a complex shape with narrow, straight and sinuous courses at three levels (fig. 2). Some places in the cave show unstable structures with very thin walls or floors, and in fact there are several places where they have collapsed.

Methods

Terrestrial laser scanning

Terrestrial laser scanning (TLS) is a light detection and ranging (Lidar) method with a ground-based platform, which enables acquiring a vast amount of point clouds having three-dimensional coordinates on a material surface. In order to measure the entire area of the cave with TLS, it is necessary to set the equipment at multiple places along the pathways. Point clouds obtained from different scan positions should then be aligned and merged with an appropriate method. Cloud-based registration which does not require the placements of target objects in each scan is applied in this study to align the point clouds of adjacent scan positions. First, a point cloud is roughly aligned to another one from an adjacent scan position by visual inspection, manual shift and rotation. The iterative closest point (ICP) method, which minimizes the distances of nearest points in different point clouds, is then applied to the point clouds to refine the alignment. This ICP procedure is repeatedly applied to point clouds to further minimize the errors of the point cloud alignments. The pair of point clouds is then aligned to another set of point clouds by ICP. Repeating these procedures, the multiple point clouds are finally merged into a single point cloud showing the entire shape of the cave.

We used Trimble TX5 for TLS (fig. 2), which is capable of measuring up to ca. 100 m of distance from the device with a 5 kg weight. Although the device has an RGB sensor inside to capture color images together with point clouds, we did not use this function because the inside area of the cave is too dark to correctly capture the visible colors. The point cloud data were initially manipulated using the bundle software Trimble RealWorks, which is capable of performing ICP registrations of individual point clouds. The resultant merged point cloud was further processed using free software including CloudCompare and Autodesk Meshmixer, which enable cleaning of the original point cloud with some noises.

3D printing and 2D slices for model construction

The cleaned point cloud was converted into a 3D mesh model having small triangle faces connecting adjacent points. The faces should have their orientation (given as "normals") to represent the direction of surface of the scanned targets. In case of a cave, walls, floors, and ceilings are supposed to have normals heading to the inner space of the cave. Here, the face of the 3D mesh model of the cave was flipped to have the negative normals of the cave surfaces. This enables to obtain a solid 3D model of the inner space of the cave, where the original cave model acts like a cast. The solid model was sent to a 3D print service, and a 1/1000 scale 3D print with nylon mate-

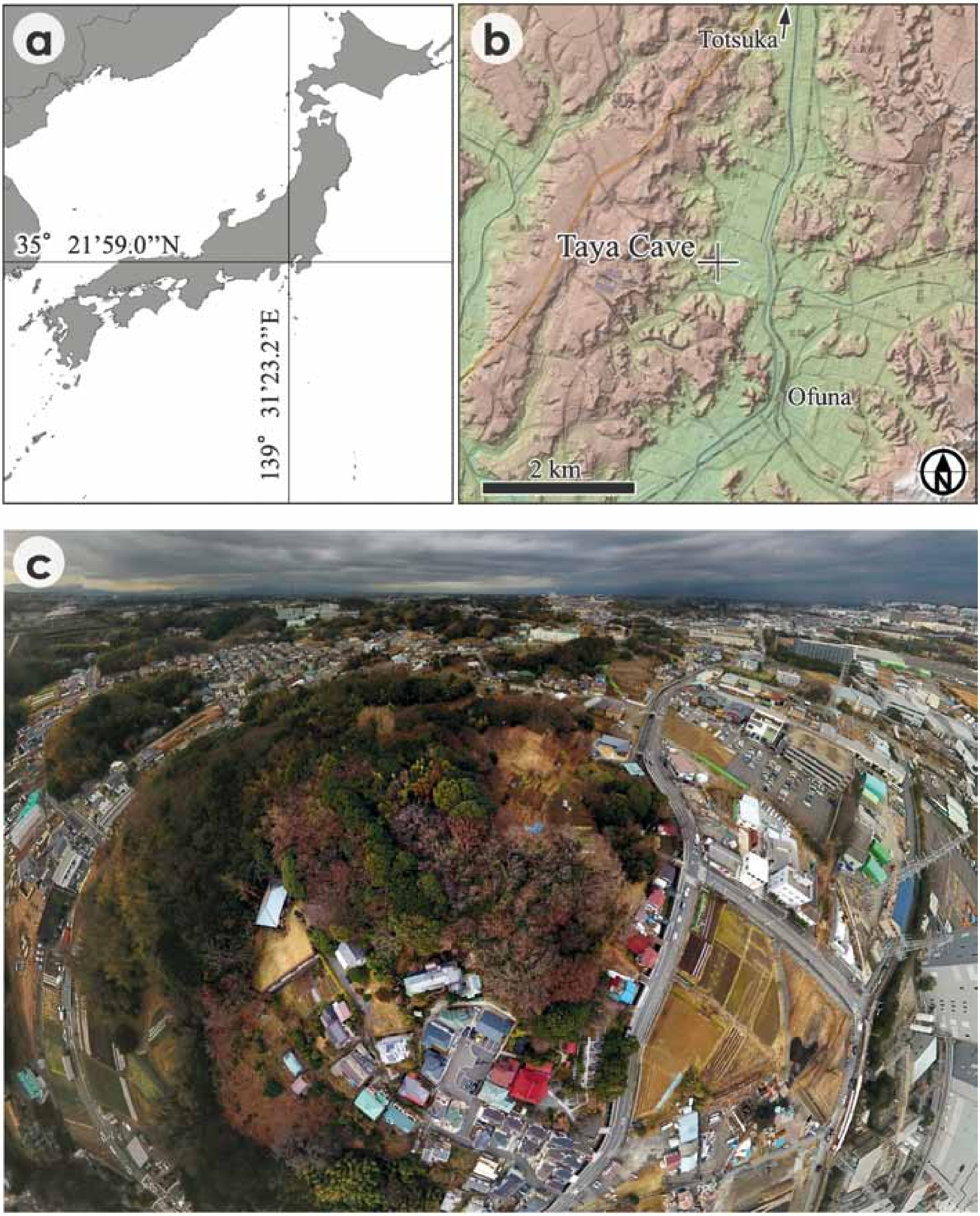

Fig. 1 – Study site. (a) The location of the study site in Japan. (b) Topographic map around the study site. The background image is based on the map given by the Geospatial Authority of Japan. (c) Aerial panorama view of the study site. Taya Cave runs through the local hill at the center of the picture (elaboration and photo: Y. S. Hayakawa).

Fig. 1 – Area di studio. (a) Localizzazione in Giappone. (b) Carta topografica nei dintorni del sito. L'immagine di sfondo è basata sulla carta fornita dalla Autorità Geospaziale del Giappone. (c) Veduta aerea del sito. Taya Cave si sviluppa attraverso la collina al centro della fotografia (elaborazione e foto: Y. S. Hayakawa).

Fig. 2 – Entrance of Taya Cave and the terrestrial laser scanner used for the topographic measurement, Trimble TX5 (photo: Y. S. Hayakawa).

Fig. 2 – Ingresso di Taya Cave, con il laser scanner terrestre usato per le misure topografiche, Trimble TX5 (foto: Y. S. Hayakawa).

rial was thus produced. The 3D print model was then used in a teaching class (6th grade in Japan school system) in an elementary school as a part of the education of local environments to help understand the entire shape of the cave.

The original 3D point cloud was also printed in a projected 2D space. By slicing the original point cloud with a certain interval along an axis, each slice of point cloud can be projected on the plane orthogonal to the axis and printed on a paper. The papers with projected slice image were then pasted on 2-mm thick boards made of styrene, and the outlines of the inner space of the cave could be cut out by handwork. The handwork was carried out by students of the local elementary school. The styrene boards with "holes" were finally aligned to represent the inner space of the cave.

Results

The measurement by TLS was carried out on 69 positions in and around the cave, where some of the scan positions were located outside of the cave (fig. 3). The measurement took a couple of days in total. The co-registration error of the individual point clouds using ICP was 7.95 mm in total. The merged point cloud has 1,039,875,102 points.

The 3D print of the solid inner space of the cave was given at a small scale (fig. 4), and used to show the complexity of the cave for the elementary school students. Although the size is very small (1/1000 of the original size, i.e., approximately 7 cm long), the 3D print model represents the characteristics of the morphology of the cave well enough to be understood by the students.

The school students also completed cutting the 2D printed boards of the projected point cloud of the cave. At the beginning of this handcraft, the students were not actually aware of what they are making. However, when it approached to the completion of the handcraft, they became to understand the structure of the cave they were making, and finally figured out the 3D shape of a part of the cave (fig. 4). The aligned boards are capable of being removed at any part, and one can see the part of the slices of the cave to understand its sliced shape.

Discussion

Complex morphology of a UBH cannot always be recognized by people, even living nearby the study site, but the 3D spatial measurement enables to visualize it and enhance their recognition. TLS is one of

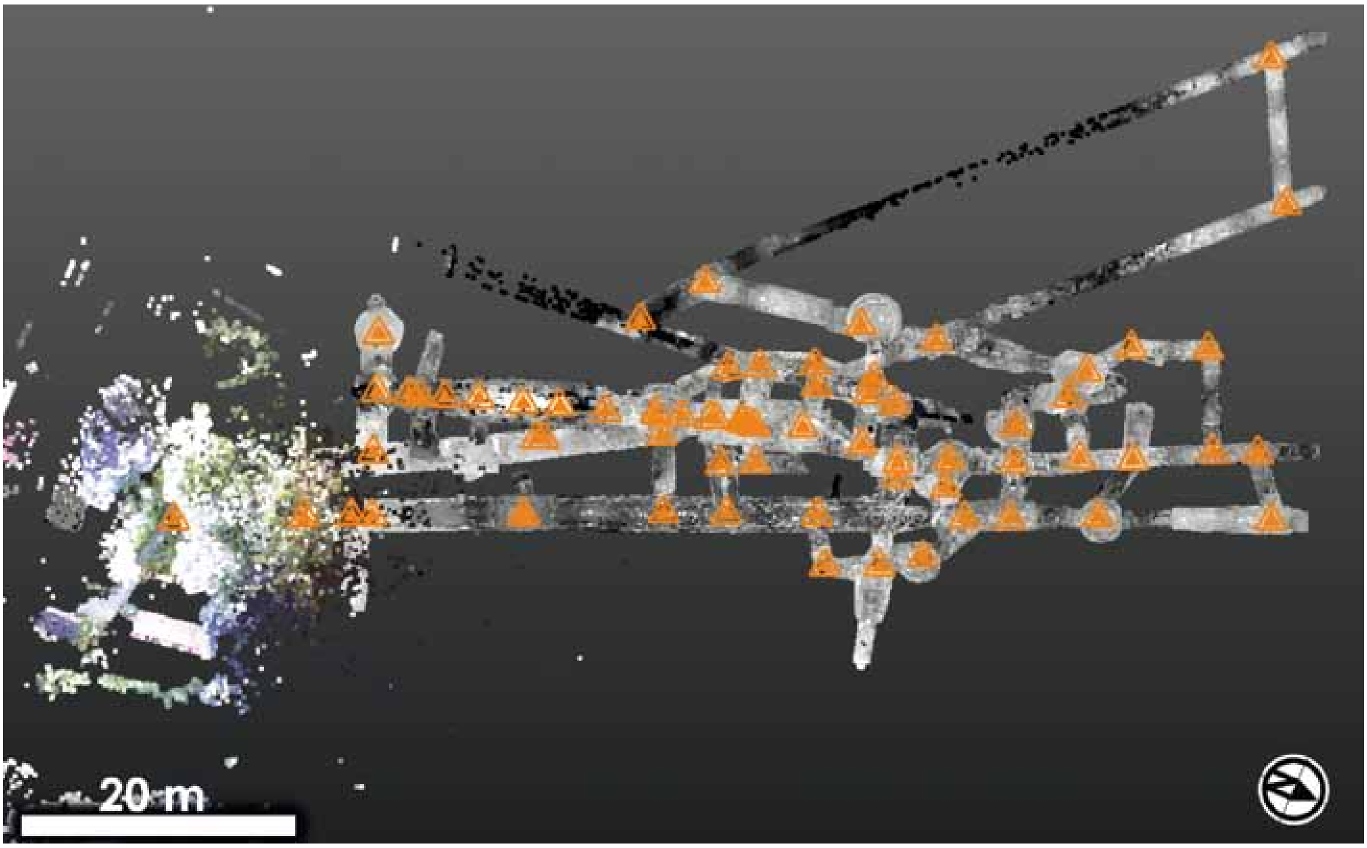

Fig. 3. Registered point cloud and scan positions of TLS. Triangles indicate the scan positions. The left-hand side of the point cloud (with colors) represents the outside area of the cave (elaboration: Y. S. Hayakawa).

Fig. 3. Nuvola di punti e posizioni di scannerizzazione con TLS. I triangoli indicano le posizioni dello scanner. La parte sinistra della nuvola di punti (con i colori) rappresenta l'area esterna alla grotta (elaborazione: Y. S. Hayakawa).

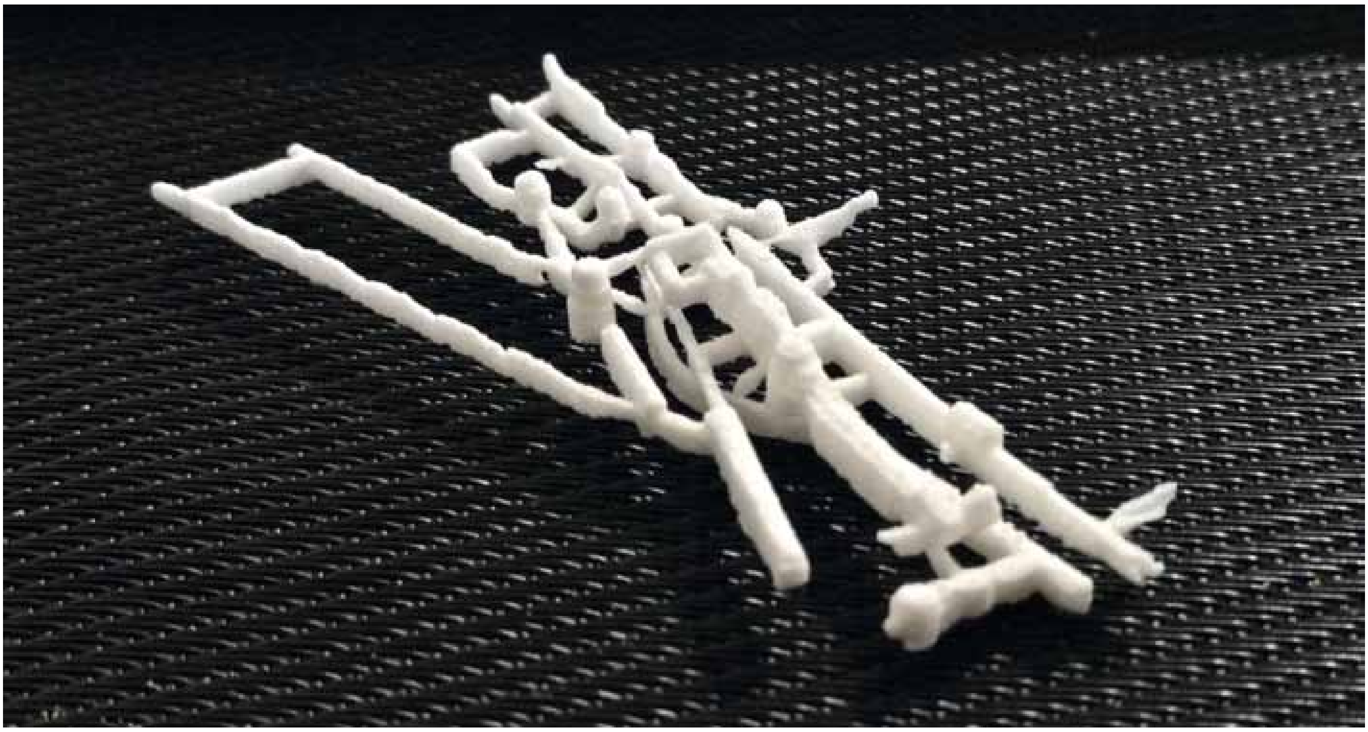

Fig. 4. 3D print model of the cave at a scale of 1/1,000. The actual size of this model is 68.6 mm x 64.3 mm x 9.9 mm (photo: Y. S. Hayakawa).

Fig. 4. 3D modello stampato della grotta, alla scala 1/1,000. Le dimensioni reali di questo modello sono 68.6 mm x 64.3 mm x 9.9 mm (foto: Y. S. Hayakawa).

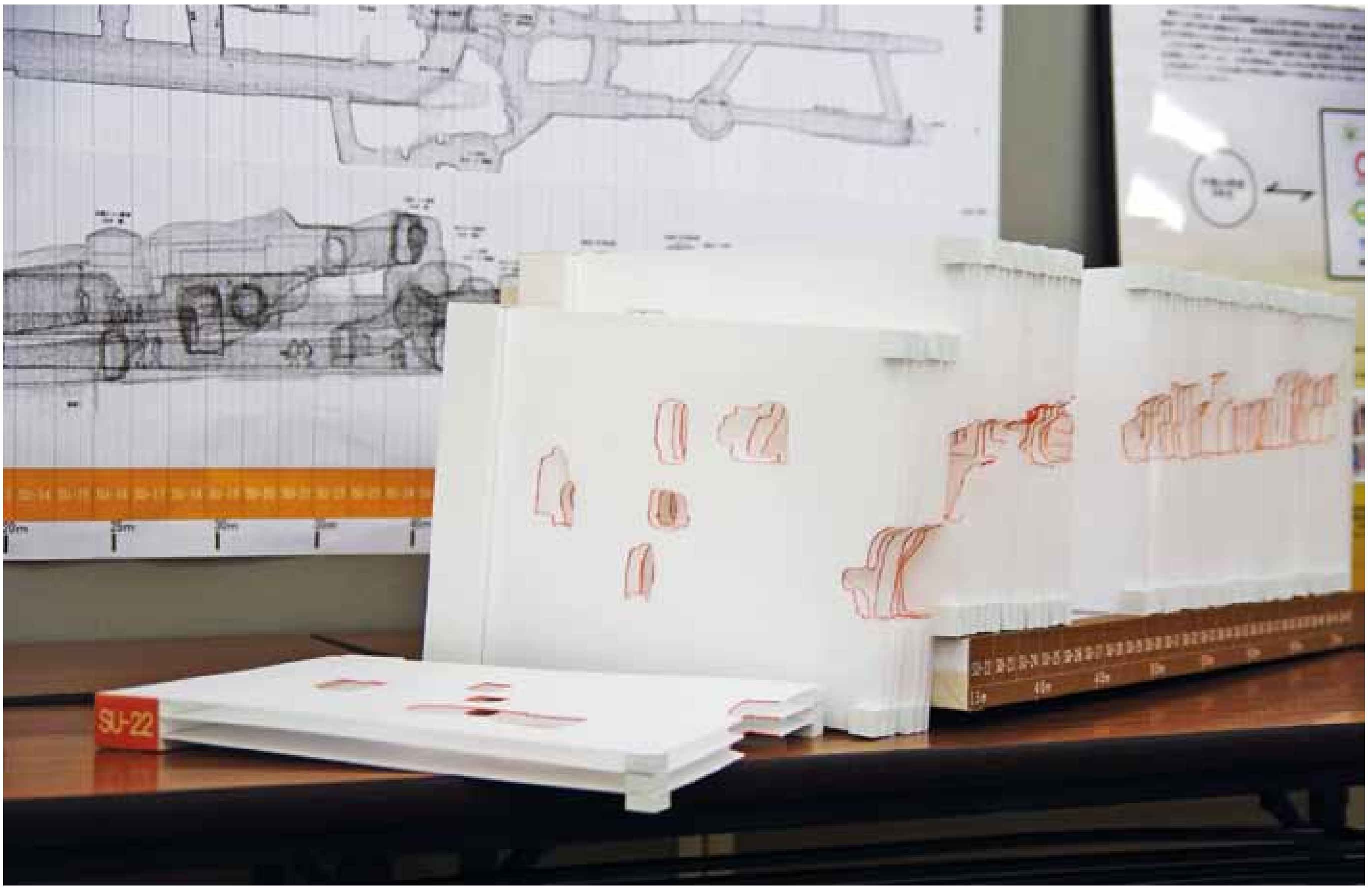

Fig. 5. Handicraft model of the cave. Thin boards of styrene with projected 2D holes of the cave are aligned to form the original 3D shape of the cave (photo: Y. S. Hayakawa).

Fig. 5. Modello artigianale della grotta. Sottili lastre di stirene con proiettati i fori in 2D della grotta sono allineati per formare la forma originale in 3D della cavità (foto: Y. S. Hayakawa).

the effective tools to perform the 3D measurement of UBHs, and this study demonstrated the use of the 3D point cloud (fig. 5) obtained by TLS for the visualization of an artificial cave with a cultural significance. In particular, creating a 3D print model and a handcraft model from the virtual data of measured 3D point cloud was supposed to be effective in disseminating the complex 3D structure of the UBH. The 3D print model can represent the complex morphology of the cave even at a small scale, whereas the handcraft model from 2D projected slice planes are more effective in understanding the detailed structure and shape of the cave by performing the handcraft by local students themselves. This procedure of understanding the structure of the cave can be interpreted as an introduction of an approach of art into an educational process. Tagami (2007) described a general model of communication in art as the coding and decryption of the sense *("kansei")* from the creator to the viewer, who both have the common base of the *kansei* (fig. 6a). Generally, the creator and viewer are different persons at different positions, and the artwork is only produced by the creator. Applying this framework to this case study, the 3D models are interpreted as the artwork, whereas the creator is replaced with the researcher or with the local students themselves. The researchers have their own academic thinking, in this case the geographical thinking. The 3D measurement is regarded as one of the research methodology of their geographical work, and the resultant 3D products can be interpreted as an artwork, particularly if they are visual enough. The visualized 3D products can be appreciated by viewers, who are unfamiliar with geographic background of the target. If the researchers are successful enough to share their knowledge or thinking in representing the 3D products, a part of the geographical thinking could be transferred to the viewers via the common base of the *kansei* (fig. 6b). The transfer of explicit academic knowledge is not always necessary in this case, but the thinking or imagination of the target material (the cave) has to be shared with the viewers with the 3D products. Moreover, if the researchers help local peoples (students) to create the artwork by themselves, like the case of the 2D slices of the cave, the viewer can also be the creator of the artwork. In that case, the artwork would help local peoples to directly understand the significance of the UBH with expanded thinking and imaginations provided by the researchers.

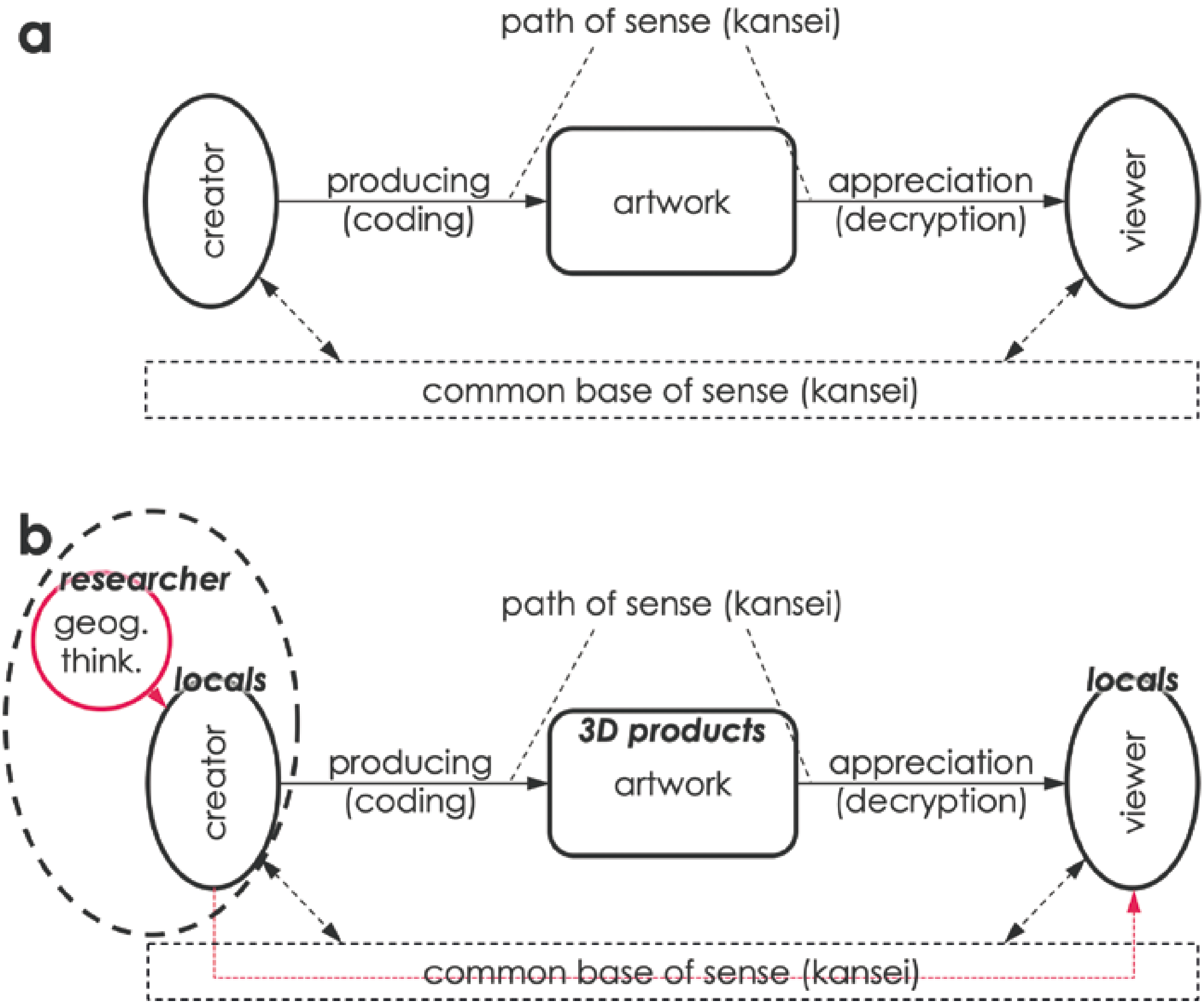

Fig. 6. Schematic illustration of communication models with artwork (elaboration: Y. S. Hayakawa).
Fig. 6. Illustrazione schematica di modelli di comunicazione mediante artwork (elaborazione: Y. S. Hayakawa).

Conclusions

In this study we demonstrated a case study of utilizing 3D products of TLS of an artificial cavity for the enhanced understandings of the value of the UBH among local people. TLS enables creating 3D products of complex underground spaces, including point cloud, solid mesh, 3D prints, and sliced/rebuilt models. The 3D products are also interpreted as artwork, which are created either by researchers or local students. The dissemination of geographical thinking and imagination was performed by the creating process of the artwork.
Various attempts to enhance the understandings of the significance of UBHs would be required to further enhance the conservation of UBHs. Although this work demonstrated an effective use of the TLS-derived 3D products of a cave in a sort of education purposes for the local people, the potential use of the 3D products would further be assessed to disseminate the knowledge, thinking, and imagination regarding UBHs with more effective and widespread approaches. Virtual reality (VR) or mixed reality (MR) approaches would help to pursue these purposes.

Acknowledgements

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