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SONAR SURVEYING OF CAVERNS AND 3D MODELLING OF ENTIRE CAVERN FIELDS

Pomiary sonarowe i modelowanie 3D wnętrza kawern

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Abstract: The echometric surveillance of caverns is especially important with regards to their safe and effective operation. As opposed to brine production caverns, storage caverns are generally subject only to convergence and they do not undergo large and irregular changes of shape under normal conditions. Echometric surveillance is therefore primarily employed to obtain proof of the cavern stability and convergence. Applying the state-of-the-art sonar technology it is possible during an echometric survey to measure and process the geometry of relevant parameters such as speed of sound, pressure and temperature with a single tool run. Today, specialized software allows us to present all the cavern field data in a common computer model, starting from the sonar survey results over the surface situation, and the well courses until the geology. In the first instance of the presentation the techniques used for surveying caverns as well as the survey procedure are described in general. Subsequently some interesting results of individual sonar surveys are presented. In the paper it is shown by means of a practical example what benefits cavern operators can derive from 3D-models of cavern field sites. Besides being useful for presentation purposes, such models can among other things help in the correlation of the survey results with the geology and support planning. Modeling is done with the CavWalk Professional software, which has been specially developed for the presentation of cavern fields. The software allows the user to undertake virtual excursions through the 3D-model at the surface as well as underground. In the spatial representation of one or several caverns the observer can move around outside and inside the caverns.

Key words: salt caverns, sonar survey, 3D modelling

Treść: Akustyczne (echometryczne) badania kawern są szczególnie ważne ze względu na zapewnienie bezpieczeństwa i efektywności ich pracy. W przeciwieństwie do kawern ługowanych w celu pozyskania solanki kawerny magazynowe ulegają zasadniczo jedynie konwergencji i nie następują w nich duże i regularne zmiany kształtu w normalnych warunkach. Nadzór echometryczny jest podstawową metodą pozyskiwania informacji o stabilności i konwergencji kawern. Podczas badania echometrycznego możliwy jest pomiar i geometryczne przetworzenie takich istotnych parametrów, jak prędkość sygnału, ciśnienie i temperatura. Obecne wyspecjalizowane oprogramowanie umożliwia przedstawienie wszystkich danych polowych z kawerny w formie modelu komputerowego, począwszy od wyników powierzchniowego profilowania akustycznego, przez profilowania otworowe aż do danych geologicznych. W pierwszej części pracy przedstawiono podstawowe techniki badań kawern i wymagane procedury, a następnie – wybrane wyniki profilowań akustycznych. Wykorzystując rzeczywiste przykłady, wykazano korzyści płynące ze znajomości modelu powierzchni kawerny dla jej operatora. Model taki jest także pomocny przy korelacji wyników profilowań akustycznych z danymi geologicznymi i przy planowaniu dalszych prac. Modelowanie wykonywane jest za pomocą oprogramowania CavInfo Professional, opracowanego specjalnie dla kawern. Oprogramowanie umożliwia użytkownikowi wirtualne podróże w modelu z powierzchni terenu i pod nią w perspektywie konwencjonalnej i rzeczywistej 3D (ujęcie stereoskopowe)

Słowa kluczowe: kawerny solne, badnia echometryczne, modelowania 3D

SONAR SURVEYING CAVERNS

Basic measurement principle

Geometric surveying of caverns is made using sonic tools on the basis of travel time measurements. In this method the time taken by an acoustic pulse to travel from the measuring tool to the cavern wall and back is determined, i.e. the measured travel time corresponds to the two-fold distance. To convert the travel time into distance it is necessary to know the acoustic velocity in the medium. This means that the accuracy and reliability of the measured cavern geometry depends directly also on the quality of the acoustic velocity determination (Fig. 1).

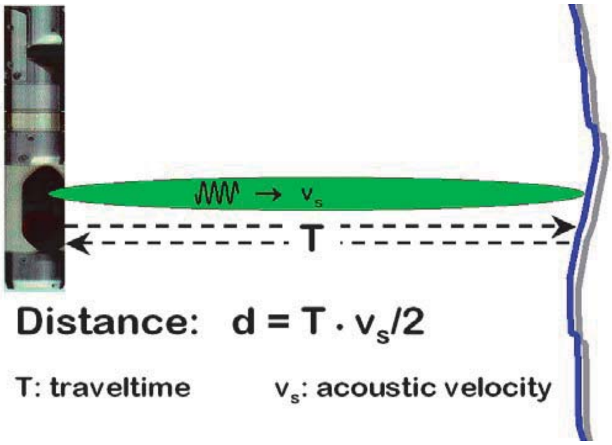

Fig. 1. Distance determination using travel time measurements

Fig. 1. Określenie odległości za pomocą pomiarów czasu przebiegu sygnału

Sonic measurements in caverns must be made in widely differing media. The range of media extends from saturated brine to liquid hydrocarbons and natural gas and even to air at atmospheric conditions. The physical conditions in a cavern depend in the first place on the actual medium, which itself is affected by any previous cavern operations as well as by the surrounding rock.

The acoustic velocity needed to convert the measured travel times into distances is subject to complex physical relationships but depends essentially on the temperature and density of the medium. Table 1 shows the typical ranges of acoustic velocity that can be expected when carrying out cavern surveys in different types of media.

Some of these distinct variations in a specific medium cannot be explained solely by changes in temperature and pressure (Fig. 2). In the case of brine the acoustic velocity is strongly dependent on the salinity and the chemical composition. An occurrence of potassium and magnesium in the brine, for instance, tends to make the acoustic velocity higher.

In liquid hydrocarbons the viscosity plays an important part. The acoustic velocity in gaseous hydrocarbons is affected not only by the pressure and temperature, but also by the moisture content and composition of the gas. Conducting logging of the cavern can help in identifying certain situations that may be occurring inside the cavern.

Table (Tabela) 1

Acoustic velocity in different media

Prędkość akustyczna w różnych mediach

Medium	Acoustic velocity [m/s]	Acoustic velocity [ft/s]
Saturated brine	1790–1900	5870–6230
Water	1450–1550	4750–5090
Oil and petroleum products	1200–1500	3940–4920
Natural gas	390–540	1280–1770
Air	330–375	1080–1230

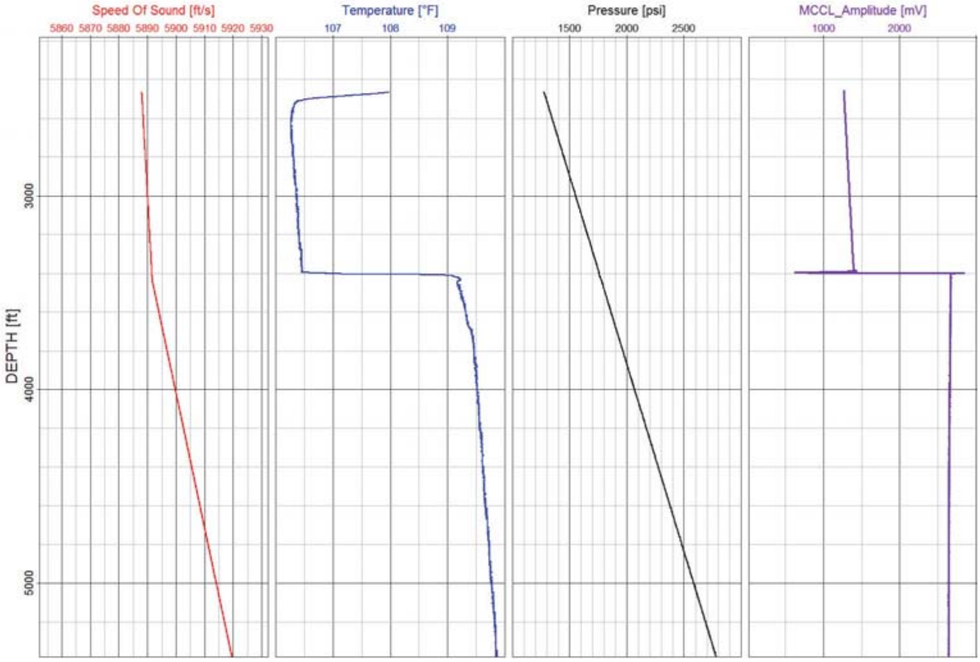

Fig. 2. Log of temperature, acoustic velocity and MCCL in a brine cavern

Fig. 2. Wykresy tempertatury, prędkości akustycznej i MCCL dla solanki w kawernie solnej

Survey procedure

In order to be able to perform optimal cavern surveying it is essential to find out the physical conditions in the cavern before the actual sonar survey is carried out. The variation of the individual parameters in the vertical survey axis should be measured by running an advance log. So as to be able to properly control the survey procedure and the subsequent interpretation of results, it is extremely important that the data are measured continuously over the entire depth range of a cavern. Information obtained at isolated points cannot provide adequate clarification of the true physical conditions.

To convert the measured travel times into distances it is necessary to know the acoustic velocity over the entire vertical extension of the cavern. In addition, the temperature distribution should be recorded as it can be used for a plausibility check of the acoustic velocity distribution. Temperature recording must be made in particular with a view to cavern sections, which have large temperature gradients or horizontal layering, because such zones must specifically be taken into account in order to achieve optimum results. If, for example, the temperature gradient is not recorded and the measurements with transducers are performed through a zone in which the temperature greatly varies, the ensuing refraction of the sonic beam would lead to an incorrect determination of the shape and volume of the cavern.

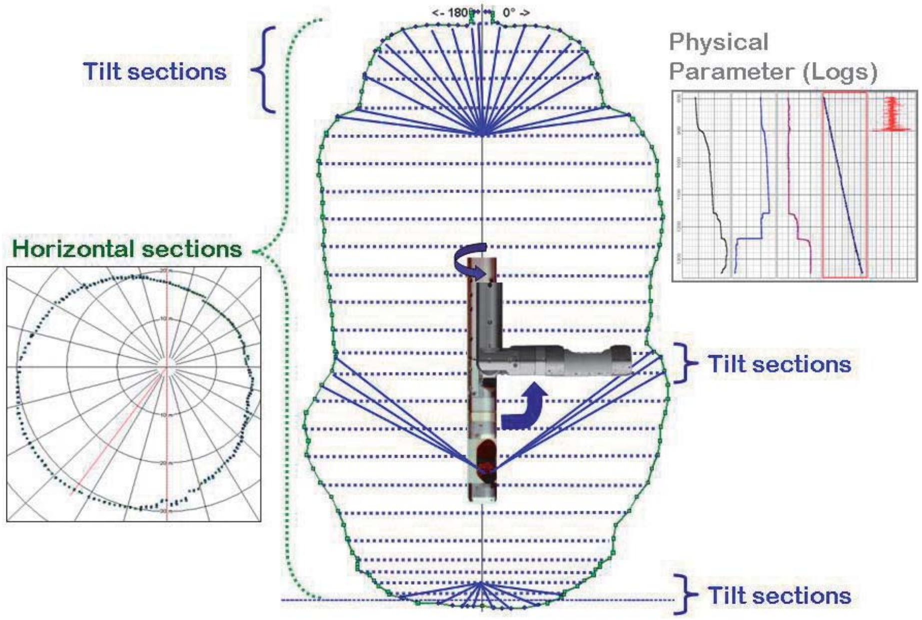

Fig. 3. Survey procedure

Fig. 3. Metodyka badań

After the initial logging, the cavern shape will be surveyed by a multitude of horizontal sections over the entire cavern depth as well as sections with titled sonar head to measure bottom, roof or any other irregularities of a cavern. The surveying principle of SOCON is based on a point-by-point sampling of the cavern wall. The measuring head is first positioned in the required direction with the required inclination and is maintained there until the point has been measured and all the necessary correlations and plausibility checks have been carried out. It is then moved to the next measuring position. Such a step-by-step rotation normally causes vibrations, which make it impossible to measure. However, this procedure is possible with SOCON tools as they are equipped with gyro stabilizers which stop tool vibration. Finally, at the end of a survey, the depth reference point is checked again to verify that the depth has been correctly tied in. Figure 3 gives an overview on the whole survey procedure.

Cavern survey analysis

The echometric survey of a storage cavern serves the combined purposes of identifying any changes in shape and also determining the actual cavern volume. The cavern convergence can be determined by comparing volumes surveyed in successive measurements.

The shape of a cavern can be more or less regular depending upon the geological situation and the specific implementation of individual leaching steps. The spectrum of possible shapes ranges from smooth regular cylindrical and pear-shaped caverns to highly irregular Christmas tree shapes. Figure 4 illustrates the roof section of a storage cavern having a very regular shape, determined using two consecutive surveys. As you can see, no significant changes in the shape took place during the observation period. Only a uniform convergence has occurred.

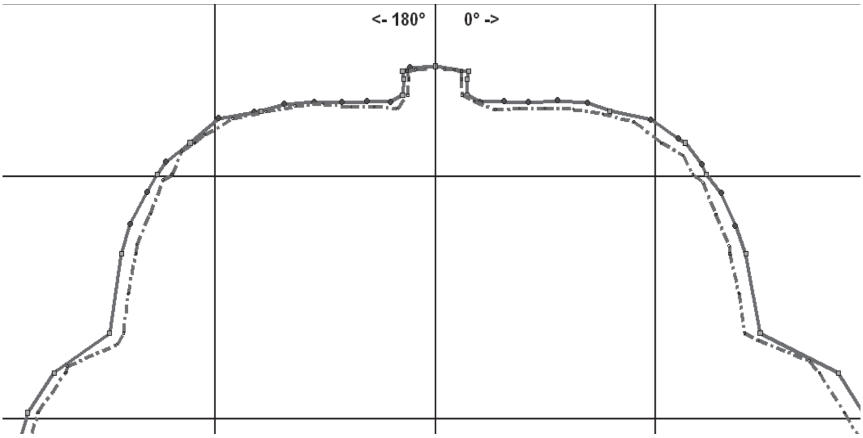

Fig. 4. Convergence in the roof zone of a cavern

Fig. 4. Konwergencja w stropowej części kawerny

Irregularly shaped caverns often have projections protruding from the wall into the cavern. Zones of this kind are obviously subject to relatively high rock stresses because they are only supported by the medium stored in the cavern. In the case of gas storage caverns in particular, where operational requirements often result in very low internal cavern pressures, this support is accordingly also minimal. The fall of such a projection often leaves behind a smoother cavern wall. Figure 5 illustrates a cavern with a somewhat irregular shape, in which spalling has taken place in the roof zone in the period between two surveys.

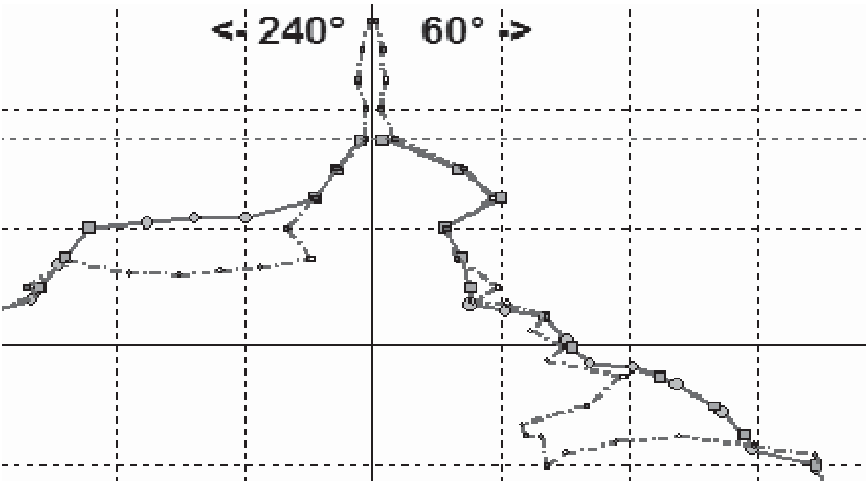

Fig. 5. Changes in a cavern roof zone (previous sonar shown as a broken line)

Fig. 5. Zmiany w stropowej części kawerny (poprzednie badania sonarem przedstawione przerywaną linią)

This example demonstrates the importance of observing and analysing roof developments during the operating phase of a storage cavern. Bearing in mind that even minor change may be crucial; the demands made on echo metric surveillance are correspondingly high.

MAPPING AND 3D-MODELLING OF ENTIRE CAVERN FIELDS

Subsurface data and information

The presentation of the geometry of a cavern on its own is no longer sufficient for carrying out further analyses. Indeed numerous other data and information must be recorded and combined with the cavern or a cavern field, then analyzed together with the cavern geometry, managed and if necessary suitably displayed. Without the application of suitable software it is nowadays not feasible to manage such a variety and volume of data.

Information relating to the subsurface includes in particular:

- geological information,
- the spatial course of boreholes over the entire length,
- data on the borehole casing and completion as well as any other operational data on the caverns, for example interface levels and inventory.

Geological data are of use and are important in the first place for the simulation and control of the leaching process, but also for analyzing any irregular development of caverns. Only a combined display of the geology and the calculated cavern geometry enables a meaningful analysis and explanation of any irregularities that occur during leaching.

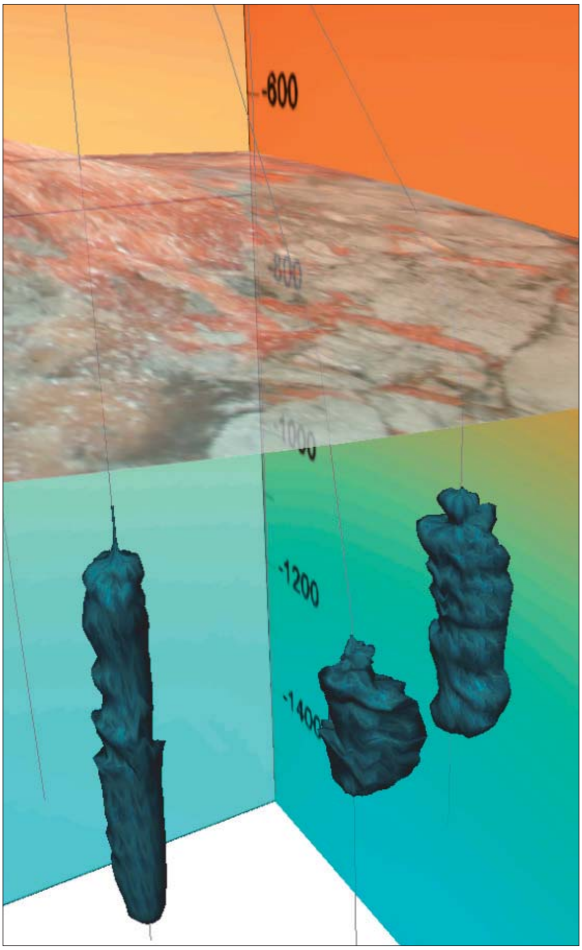

Fig. 6. Caverns with deviated boreholes

Fig. 6. Kawerny powstałe z odchylonych otworów

The spatial position of a borehole over its length is essential for correctly locating a cavern within a cavern field. This is because only when a cavern survey is accurately tied to the location of the reference point – generally the lowest cemented casing shoe – is it possible to precisely determine the thickness of the support pillars and the shortest intervals between adjacent caverns. A prerequisite for this is that the true vertical depths (TVD) are calculated from the deviation measurements made for the reference points and that the results of the cavern survey are then referred to these adjusted reference points.

As soon as boreholes significantly stray from the vertical or are deviated (Fig. 6), a comparison with measured depths (MD) leads to incorrect results. To make it at all possible to present caverns in the correct spatial location, the sonar tool used must be fitted with a CCL or MCCL (multiple casing collar locator) sensor; it is this tool, which refers the cavern data to the TVD of a casing shoe.

A basic requirement for creating a combined 3D-model is that all the data are acquired in a uniform coordinate system. The work involved here can be easily and efficiently carried out for the data acquired underground using the CavMap program. The situation at the surface can be integrated by referring to maps. Figure 7 shows by way of example in a plan view the data acquired with CavMap for a cavern field.

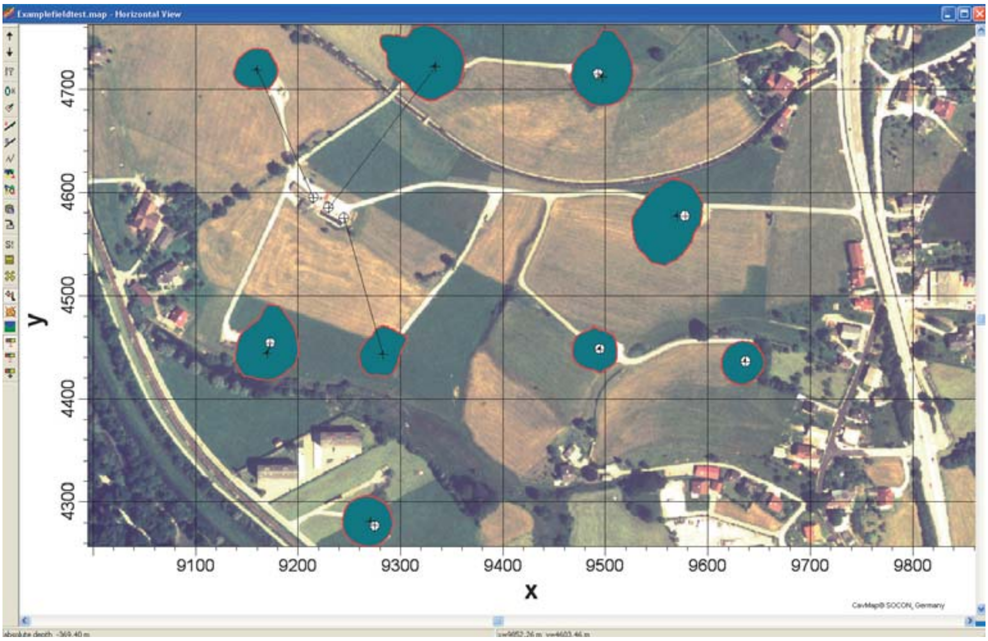

Fig. 7. Display of a cavern field using CavMap

Fig. 7. Wskazanie obszarów kawern za pomocą programu CavMap

In the next step on the way to a 3D-model the data are appropriately prepared for the 3D-modeling by the CavMap program and subsequently are available for the straightforward transfer into the 3D-model of CavWalk Professional. For this no special knowledge of 3D-modeling is required.

Modelling the situation at the surface

In addition to the subsurface data and information, the situation at the surface can also be integrated into a 3D-model. Incorporating this information is of interest not only for company-internal reasons – for instance for planning new site facilities – as it is also becoming increasingly important for informing the public and for use in official approval procedures.

Besides any on-site buildings and other operational facilities, of particular relevance in this respect are also the surface utility networks. Suitable programs for acquiring data of such networks are all those that have a dxf interface, because the dxf standard is used as the input format into the 3D-model of CavWalk Professional. Figure 8 shows, as an example, the modeling of buildings and pipelines at the surface of SOCON's former works site.

Fig. 8. 3D-model of site buildings

Fig. 8. Modelowanie 3D położenia budynków

Generation of a combined 3D-model of a cavern field

Based on the data acquired with CavMap, the 3D-modeling is performed using the CavWalk Professional program. All the data acquired previously with CavMap are now automatically combined with the data of the surface model to form a combined 3D-model (Fig. 9). No knowledge of 3D-modeling of objects is necessary for this as the procedure is done nearly automatically.

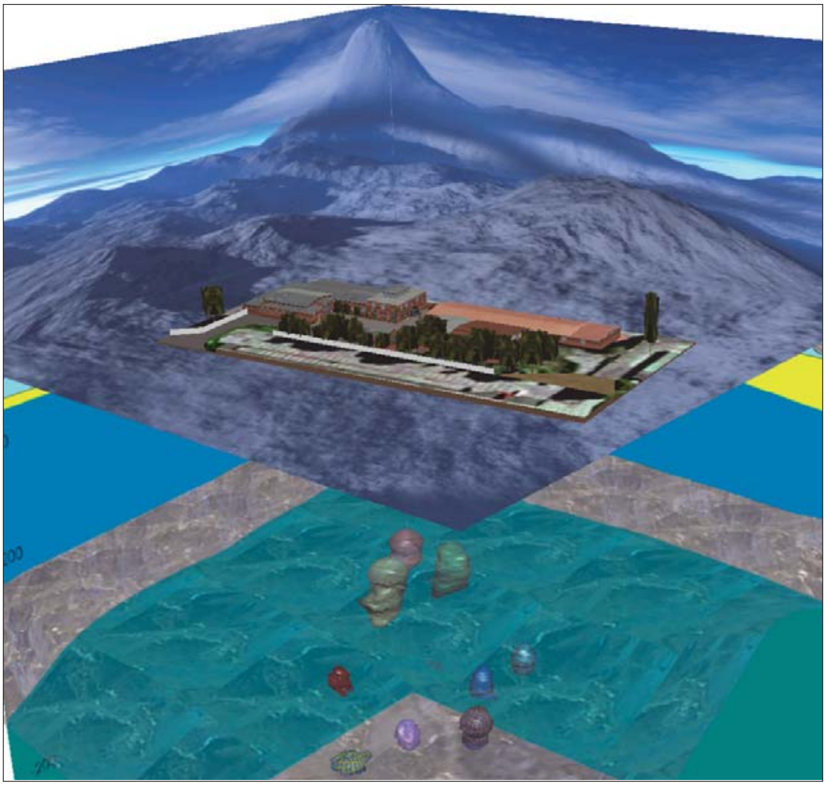

Fig. 9. Combined 3D-model of a cavern field with CavWalk Professional

Fig. 9. Połączony model 3D pola kawern z zastosowaniem CavWalk Professional

During the automatic modelling first of all the previously selected cavern measurements are transferred to a uniform three-dimensional coordinate system considering the coordinates of their reference points. The 3D-visualization of the caverns, together with the positions of the boreholes along their entire length, is generated within a cube, the boundaries of which can be a map or a picture of the Earth's surface at the top and geological sections at the sides.

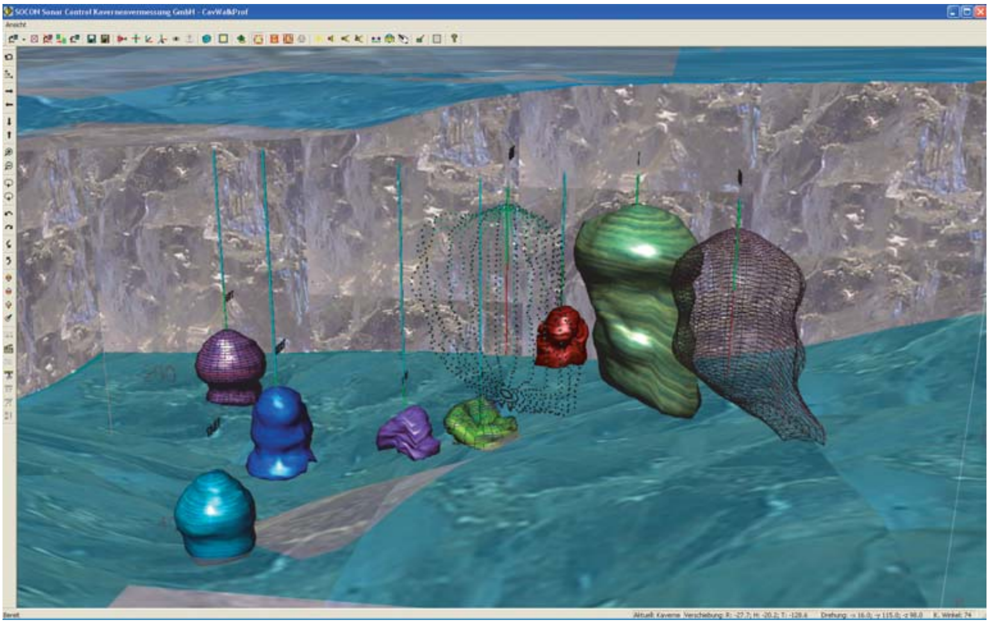

Fig. 10. 3D-model of a cavern system with CavWalk Professional

Fig. 10. Model 3D pola kawern z zastosowaniem CavWalk Professional

Normally geological information exists only for specific points. However, as part of this modeling the relevant geological layers are automatically determined on the basis of the available data. In the case of the model shown in figure 10 these layers are the bottom interface of the Quaternary as well as the top and bottom of the salt deposit. These surfaces can be displayed either as surface models or as lattice or line models. By displaying the geological layers transparently the three-dimensional effect of the model can be improved significantly. The same is true for the caverns, which can also be displayed as scattergrams. In this case every individual survey value is represented by a point. This type of display gives an idea of the actual survey point density and as such of the reliability of the cavern shape visualized.

CavWalk Professional allows the user now to take a virtual tour not only through the subsurface but also around the surface of the combined 3D-model. The observer can move any way he wants outside or inside the model simply at the movement of the mouse. In this way pseudo-realistic interior views of caverns and views of objects on the surface can be observed. From the models, 3D-animations can be created, saved and shown as films.

SUMMARY

Applying software that has been specially developed for cavern fields it is possible to generate 3D-models of entire cavern fields within a short time and with a minimum

of manpower. The procedure using the CavMap and CavWalk Professional programs was explained and examples were given to illustrate how such models can be expediently and effectively used for solving difficulties in operational planning.

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