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GROUND-FREEZING ON ARCHAEOLOGICAL EXCAVATIONS: LIFTING A MEDIEVAL CHALICE FROM ST GILES HOSPITAL, BROUGH.

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Summary

The paper examines the feasibility of using ground-freezing as a technique for lifting artefacts from archaeological excavations, and its advantages over other lifting techniques. The different ground-freezing techniques are discussed, and the chosen technique (using solid CO_2) is described in detail. The second part of the paper documents the use of ground-freezing in the field, to lift a Medieval mortuary chalice.

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GROUND-FREEZING ON ARCHAEOLOGICAL EXCAVATIONS : LIFTING A MEDIEVAL CHALICE FROM ST GILES HOSPITAL, BROUGH.

Ground-freezing as a technique for the retrieval of information from archaeological excavations has attracted much interest from conservators. However, the method is not in widespread use, due probably to a lack of published material describing the practical processes involved, and concern about the effects of a freeze-thaw cycle upon archaeological material. The study of the subject may be divided into two areas :

1. Ground-freezing on archaeological excavations : An examination of the feasibility of using the freeze-lifting method, and the development of a methodology for the process.

2. The effects of freezing on archaeological materials : An examination of the effect of a freeze-thaw cycle upon the physical and chemical structure of archaeological materials.

The first part of this paper concerns itself with study area one.

Freeze-lifting.

The basic concept is the freezing of the area of ground in which the artefact/material of interest is situated, thereby imparting rigidity and strength to the ground, enabling the artefact to be lifted undisturbed within the confines of its immediate environment. The material is then stored frozen until such time as excavation and examination under laboratory conditions can be carried out, at which point the excavated block is allowed to thaw.

Possible advantages of using ground-freezing as a method of lifting archaeological materials.

The ground-freezing processes which will be reported in this paper are based upon the use of solid carbon dioxide, or a mixture of solid carbon dioxide and industrial methylated spirits, to produce the frozen state. Briefly, this entails the direct application of the solid carbon dioxide to the ground surface, the separation of the frozen block from its surroundings, and its storage in a domestic freezer until such time as the material can be worked on.

The possible advantages of such a lifting process, as opposed to presently-used methods (eg encasement of material and soil block in polyurethane foam or plaster of Paris) are as follows :

1. No disturbance to the surrounding stratigraphy other than the extraction of that area immediately surrounding the artefact. The stratigraphy within the extracted area will not be disturbed, and its size may be controlled as desired in order to include or exclude surrounding material. There is no need for a complete excavation around the artefact in order to isolate it upon a soil pedestal.

2. The preparation of the ground prior to freezing is minimal, and therefore the time taken by the operation is entirely dependent upon the time needed for the freezing process.

3. Once lifted, initial examination of the artefact and associated material should be more convenient as there will be no additional support surrounding or masking it. For example, whilst frozen, the soil block may be x-radiographed from different angles, in order to examine the artefact's relationship with the surrounding material. In addition, the excavation of the artefact from its surroundings may be undertaken from the angle considered capable of yielding the maximum amount of information.

4. The storage of the material in a domestic freezer, at approximately -20oC, eliminates the need for constant monitoring of the environment. There is no risk of mould growth, and chemical reaction rates will be considerably reduced. Care must be taken in packing the material, however, to avoid any possibiblity of it freeze-drying if stored for a long period of time.

History of ground-freezing.

Artificial ground-freezing has been used in engineering since 1862, for the stabilisation of soils prior to the excavation of tunnels, mine-shafts, and the laying of building foundations. The technique patented in Germany in 1883 by Poetsch, using the circulation of brine through pipes sunk into the ground is, with some improvements, still the main method in use today. Freezing with liquid nitrogen was first used in France in 1962 for the construction of a section of the Paris Metro (Jones JS and Brown RE 1970).

The published material on the use of ground-freezing as an aid to the lifting of archaeological materials appears to be very limited. The technique was first used in Italy in 1937 under orders of Mussolini for the lifting of the Ara Pacis Augustae - the Altar of Augustan Peace. This altar was discovered in marshy ground below a Renaissance palace, and attempts at excavation were hampered by continual water build-up. Scaffolding was erected to support the palace, and the area beneath was frozen using enormous refrigeration plants. The frozen earth, water and sculpture were then cut into sections and dragged free of their surroundings, after which they were reassembled (Chamberlain ER 1979).

In the 1970's, there was further interest taken in freeze-lifting, particularly in Scandinavia. However, published material only mentions its possible advantages for the lifting of burials for study in the laboratory (Nylen E 1975), and no details are given as to the methods or techniques used.

The Principle of ground-freezing.

Soil may be defined as a natural aggregate of mineral grains, with or without organic constituents, that can be separated by gentle mechanical means, such as agitation in water. It may consist of either a three-phase system comprising solid mineral matter, water, air or other gases, or a two-phase system comprising mineral matter and water. In this instance the soil is said to be saturated.

The basic concept in ground-freezing is the removal of heat from the two or three-phase soil system, thus causing the water present to transform into ice, and to act as a binding agent increasing the strength of the ground. Cohesion in frozen ground is due to :-

1. the molecular forces of attraction between the soil particles.
2. the physical and chemical cementation of the soil particles.
3. particle cementation by the formation of ice in the soil voids.

The compressive and tensile strength of the frozen ground depends upon the freezing temperature, the moisture content and the nature of the soil. Its strength will increase with a decrease in freezing temperature and an increase in moisture content up to saturation point, whereupon there will be a decrease in strength.

Thermal Considerations and Calculations.

The determination of the depth and rate of freezing penetration in soils requires a knowledge of the thermal properties of water and soils, the properties which influence freezing. These are as follows :-

- the latent heat of fusion in soil moisture;
- the heat capacity of water in soil (volumetric heat capacity and mass heat capacity);
- the thermal conductivity of the soil;

other related properties which are of importance are the specific heat and the thermal diffusivity.

As the freezing penetration of soils is a physical process, it can be treated mathematically with some degree of accuracy. In the analyses of the various heat transfer problems, the steady-state flow of heat and the unsteady state heat conduction are theories which are generally applicable. These can be developed for the study of specific heat transfer problems in soil. Two further theories which are of particular use for the calculation of the depth and rate of freezing penetration in soils are those of F. Neumann (Jumikis AR 1966) and J.Stefan (Bouyoucos GJ 1921). Both these theories were developed for the study of the formation of ice on still water, but if soil geotechnical constants are properly fitted into the formulae, they can be applied to freezing penetration in soils.

In general, these theories show that the ground-freezing rates will vary with the type of soil, ie different soils will have different specific heat and thermal conductivity. The rate will also depend upon the moisture content of the soil - the higher the moisture content, the slower the freezing rate.

Ground Movements.

The potential movement of the ground during the freezing and thawing processes needs to be considered in respect to the possible disturbance to artefacts and associated material within the soil block. The two potential sources of movement are from frost expansion during the freezing period, and consolidation of the soil during the thawing period. Consolidation and 'slumping' of the soil during thawing could be particularly damaging once a soil block has been isolated from its surroundings, if there is no provision for support around the original contours of the frozen block.

Consideration of existing ground-freezing processes for archaeological excavations.

Requirements.

In choosing a ground-freezing process for use on archaeological excavations, the following factors have to be taken into consideration:

1. the time required to achieve the desired extent of freezing within the soil system.
2. the disturbance caused to the excavation, particularly the surrounding stratigraphy.
3. the availability of equipment and materials.
4. the costs involved in producing the frozen state.
5. the scale of the lifting operation.

Ground-freezing processes.

1. The Refrigeration System :

This system requires a certain amount of hardware, including a refrigeration plant, pumps and pipes for circulating the coolant. As the use envisaged on archaeological excavations is on a very small scale compared with engineering usage, then there would be a need for the design and construction of special equipment. The operating temperature of the coolant is in the region of -20oC to -40oC, thus the ground-freezing process is relatively slow when compared with alternative methods.

2. Liquid Nitrogen :

The equipment required for the injection of the liquid nitrogen into the ground is relatively simple, comprising a pump capable of operating at low temperatures, and the delivery tubes and pipes. However, as with the refrigeration system, no ready-made equipment is available for working on a small-scale, and therefore design, manufacture and testing of equipment would be necessary.

Liquid nitrogen does have certain advantages over alternative methods, however, and should perhaps be considered in future development of the freeze-lifting technique. Its main advantage is that it has a boiling point of -196oC, and therefore from thermal considerations it can be shown to produce much faster freezing times than the alternative methods. Being widely used in the chemical and engineering industries, liquid nitrogen is readily available and easily transportable, given the correct containers. It is, however, costly.

3. Solid Carbon Dioxide.

Carbon dioxide has a freezing point of -79oC, and is therefore capable of producing faster freezing times than the refrigeration systems. Being a solid, its use is restricted to surface applications, and so the time for freezing to any great depth would probably be restrictive. However, it does not require any specialised equipment for storage, transportation or application. It is widely used in industry, and readily available, and its cost is relatively low, particularly if bought in bulk.

4. Solid Carbon Dioxide/Industrial Methylated Spirits.

The disadvantage of using solid CO_2 alone is that being a solid, the thermal contact and corresponding heat transfer between the CO_2 and the material to be cooled is not at an optimum level, and is also restricted to the ground surface. The use of a solid CO_2/industrial methylated spirits mixture was therefore considered as a method of increasing the thermal contact and heat transfer, and also of producing faster freezing times by penetration into the soil.

Choice of ground-freezing process.

Solid carbon dioxide was chosen as the ground-freezing medium, based upon its advantages of low cost, availability, and the non-requirement of support facilities (delivery pumps, refrigeration units etc.)

The relatively slow freeze time when using carbon dioxide alone, as compared to say liquid nitrogen, was considered to be of secondary importance in the evaluation of the basic concept of freeze-lifting.

Relevant properties of solid carbon dioxide.

Carbon dioxide can exist in three states : as a gas, a liquid or a solid.

As a gas at normal temperatures and pressures, CO_2 is colourless with a slightly pungent odour at high concentrations. It is heavier than air, and when released to the atmosphere will spread along the ground, and collect in pits or other low-level enclosed spaces. Carbon dioxide cannot exist as a liquid at atmospheric pressure.

Solid CO_2 is manufactured by compressing and cooling CO_2 gas to a liquid. The high pressure is then reduced and the cold carbon dioxide expands rapidly and returns to vapour. The evaporation causes a lowering of the temperature of the remaining liquid, which freezes to a snow-like solid. The CO_2 snow is then compacted under high pressure into blocks. The surface temperature of the CO_2 blocks is -78.5oC. Under ambient conditions, sublimation of the solid CO_2 takes place, leaving no residue, as it changes directly back to a gas.

The latent heat of vaporisation of solid carbon dioxide is 572 KJ/Kg, which produces a very high cooling effect for a given volume. It is therefore capable of absorbing approximately twice as much heat from its surroundings as water ice.

In general, carbon dioxide can be considered as unreactive, and will not support combustion. It will only react, under certain conditions of temperature and pressure, with other substances which are highly reactive themselves, eg. sodium, magnesium etc.

Storage.

Under normal conditions of temperature and pressure, the sublimation of solid carbon dioxide will continue even where heavy insulation is provided. However, storage in suitably insulated containers can reduce the losses to as little as 3-4% per day. Sealed gas-tight containers must not be used as pressure build-up can be as great as 1305 lb/in2.

Transport.

Care must be taken in transporting solid carbon dioxide, as there is a risk of a build-up of gas if ventilation is limited. It should never be carried adjacent to the driver, and adequate ventilation should be provided at all times.

Safety aspects.

Although the use of solid carbon dioxide presents no major safety problems, certain precautions must be observed :
1. It must not be kept in sealed gas-tight containers, as a build-up of gas pressure may lead to an explosion.
2. In handling, some form of protection must be worn, as contact with bare skin can cause frost bite.
3. Carbon dioxide gas is heavier than air, so adequate ventilation must be provided to avoid a build-up of high concentrations at low levels. Although CO_2 is not considered a toxic gas, an accumulation of the gas will displace air, and so reduce the oxygen available. Inhalation has the effect of stimulating respiration, and may also produce mild narcotic effects.

Availabilty.

Solid carbon dioxide is manufactured by the Distillers Company (Carbon Dioxide) Limited, under the trade name of Cardice. It is supplied as either blocks of 11.5kg, which may be easily broken and crushed with a hammer, or as small cylindrical pellets. The pellets are packed in polythene bags, each containing 11.5kg. Cardice is available from many depots and agencies throughout Great Britain, details of which can be obtained from the regional sales offices. The price is dependent upon the quantity ordered, and at the time of writing could be obtained for as little as £10 for a block weighing 11.5kg. Pellets of solid carbon dioxide can also be produced as required by a small unit called a Snowpack, which works off any standard CO_2 gas cylinder.

Experience in obtaining Cardice at very short notice has shown that many industrial users, if approached in an appropriate manner, willingly supply the small quantities required for lifting archaeological remains.

Experiments in ground-freezing and freeze-lifting.

Once the choice of solid CO2 or a solid CO2/methylated spirits mix had been made as the most suitable medium for freeze-lifting on small-scale archaeological excavations, experimental laboratory procedures were made to test out a number of aspects of the technique.

It was thought that to make thermal calculations, which rely among other things upon a prior knowledge of the soil type, its thermal properties and moisture content, was impractical within a field situation, but might be of use as a general guide from which to start experimentation. A series of controlled laboratory experiments was therefore designed to:

1. evaluate the freezing action and freezing time in differing soil types with differing moisture content.
2. enable an estimate to be made of the quantity of solid carbon dioxide required to freeze a certain ground volume.
3. determine the method by which the frozen ground could be lifted free of its surroundings.
4. determine the most suitable means of packing the frozen ground block whilst in transit and storage.

The results of these experiments, and the details of the procedures followed may be found in P. Clogg's paper (Clogg PW, forthcoming). These controlled laboratory experiments were then followed by a series of freeze-lifting field trials on archaeological sites, when the opportunity arose over the excavation season. A total of six experimental lifting operations were carried out on excavations at Shiptonthorpe, East Yorkshire, and Stanwick, North Yorkshire.

Freeze-lifting a chalice from St Giles Hospital, Brough, N. Yorks.

The Site

In 1990, a team of freelance archaeologists, on behalf of North Yorkshire County Council, was engaged on the third and final season's excavation near Brompton-on-Swale in North Yorkshire.

The site, known as St Giles' Hospital, was a small rural hospital, flourishing from its foundation sometime before 1181, and declining from the fifteenth century. It served the dual function of providing care for the sick and infirm, and also hospitality for travellers. The excavation had Rescue funding from English Heritage, as the site is in danger of erosion from the River Swale, which runs very close by (Cardwell,P, forthcoming).

During this third season, the hospital chapel and its surroundings were being excavated, and the area under investigation proved to contain part of the cemetery. A total of 42 burials were revealed, both inside and outside the chapel walls.

Two of these burials were included fragmentary grave goods, and these finds enabled us to test out the freeze-lifting technique in the field, and to compare it with another commonly-used lifting technique.

Lifting with Plaster of Paris

The first burial was of a reasonably well-preserved adult, with two metal objects lying in the abdominal region. The burial extended out under the western wall of the chapel building, the wall having been rebuilt over the earlier burial at some point in the chapel's history. This western wall of the chapel was not being removed during the excavation, which meant that the burial was very awkwardly placed for a lifting operation, with the grave goods actually under the stones of the wall. Lifting this assemblage of grave goods was approached in the conventional manner, and a covering of plaster of Paris and bandages was applied to the objects, after clearing a space in the skeletal remains around them. The plaster-covered soil block was difficult to extract from the ground, as it was lying on the rest of the skeleton, but it was removed along with some of the vertebrae, and part of a rib, and returned to the conservation lab at Durham for examination.

Preparing to use the freeze-lifting technique

Some weeks later, the excavators informed us that another burial with grave goods had been uncovered, and after visiting the site to examine the find, it was decided to lift this assemblage using the freeze-lifting technique. The dimensions of the material to be lifted were not very great, and no problems with freezing to the required ground depth were envisaged. Therefore, it was decided to use solid carbon dioxide alone as the freezing medium, as the greater soil penetration afforded by the solid CO2/methylated spirits mix was not needed. The basic technique was to be the same as for the laboratory experiments...A portable temperature probe was not available, so the depth of freezing action was to be estimated by time, using data obtained from the laboratory experiment series. Six kg of solid carbon dioxide was purchased and put into a Dilvac insulated flask. This flask has a heavy, rubber-sealed lid, but is not gas-tight, to avoid the build-up of pressure from the CO2 gas. Polythene bubble pack was placed on top of the solid CO2 inside the flask, to provide some extra insulation.

The burial was of a well-preserved adult, with metal objects in the abdominal region. These objects did not appear to be in such a good state of preservation as those from the first burial. The burial was lying at an angle to the edge of the excavation trench, just outside the south wall of the chapel, with the lower part of the skeleton still in the section.

Freeze-lifting

The area where the grave goods lay among the skeleton had already been cleaned back by the excavator to reveal the metalwork, which spread out for no more than 200mm in any direction, and lay on top of the vertebrae, below the ribs and above the pelvis. The soil was a fairly light sandy silt, with a few small stones mixed in, but there were no large stones in the immediate vicinity of the grave goods. In order to keep the fragmentary metalwork as secure as possible, the objects which had been revealed were covered over again with soil, and the top surface of the area levelled out.

The dimensions of the required block were decided upon, and an approximately circular area was defined by inserting the blade of a knife into the soil. Next, flexible aluminium strip, 150mm wide x 1mm thick was pushed into this cut, with around 45mm of the strip projecting above the ground surface. The crushed, solid CO_2 was then poured from the flask onto the ground to fill the aluminium ring. The CO_2 was covered with polythene bubble pack and a layer of 18mm thick polyethylene foam for insulation.

Again, the vertebrae of the skeleton lay beneath the artefacts, hopefully separated from them by a thin layer of soil, though it was not possible to check this without disturbing the grave goods. It was hoped to be able to lift the frozen artefacts and soil, but to leave behind the vertebrae. The depth to be frozen was around 120mm, and using the data gathered from the laboratory freeze-lifting experiments, a waiting time of 15 minutes was calculated. At the end of this time, a trowel was inserted beneath the frozen block, to lever it away from the ground surface. This was followed by a spade, and the block was successfully separated from the unfrozen ground surface, and lifted out on the spade, leaving behind the vertebra of the skeleton.

A wooden tray lined with polythene bubble pack had been brought along to receive the frozen block. The block was surrounded by rings of corrugated cardboard, with polystyrene chips and polythene bubble pack providing insulation for its journey back to the laboratory. It was stored, still wrapped to prevent freeze-drying, in a chest freezer in the Archaeology Dept, Durham University, to await examination.

Examination of the lifted blocks.

Both blocks from the site were examined and excavated in the laboratory, which highlighted further advantages of the freeze-lifting technique.

Before excavation of the blocks, it was decided to make X-radiographs of them to determine the number of objects in each block, their orientation, and if possible their relationship to each other. This was done for the frozen block, but the one lifted with plaster bandages proved too bulky to fit into the chamber of the X-ray machine. Thus, we had the advantage of beginning the excavation of the frozen block with some indication of what might be found.

When the polythene insulation had been removed from the frozen block, it was possible to see its dimensions, and to provide extra support around the block, in the form of corrugated cardboard and foam, whilst it was still frozen, to prevent the soil block collapsing or distorting as it thawed. The block was also further supported by the ring of aluminium strip which was still in situ.

Removal of the plaster of Paris and bandages took some time, and it was not so easy to support the soil block when they had been removed, though as the soil had been damp when lifted, it did not immediately begin to slump when the plaster support was removed, and it was possible to prevent the block from collapsing, and allow it to be excavated.

The grave goods

Both the objects lifted proved to be mortuary chalices. The burials were those of priests, and the grave goods denoted this. However, instead of burying precious chalices made of metals such as silver, low-grade lead alloy examples were produced during the Medieval period, specifically for burial purposes. Energy dispersive x-ray fluorescent analyses were done of both chalices, which proved to be made from lead/tin alloys, with a very small percentage of silver added. There was no copper in the objects.

Advantages of the freeze-lifting technique.

Several advantages of the freeze-lifting technique over the plaster bandage method were perceived as a result of lifting the grave goods from the St Giles Hospital site. The main ones can be summarised as follows :

1. Freeze-lifting causes less disturbance to site stratigraphy.
2. It keeps the stratigraphy immediately around the object intact.
3. For small objects, especially, the lifting procedure is much quicker.
4. The resulting block is less bulky, and therefore easier to remove from the site and to store.
5. The smaller frozen block is more easily photographed, X-radiographed, and examined without disturbance.
6. Excavation under laboratory conditions is quicker and easier without the plaster or polyurethane foam covering.

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