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OVERVIEW OF LOW-LEVEL RADIOACTIVE WASTE DISPOSAL FACILITIES SUBSIDENCE

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ABSTRACT

The result of a case study of the Sheffield, Illinois, waste disposal facility, and literature reviews on problems at waste disposal facilities are presented. The types of problems, causes of the problems, and approaches to mitigate the problems are evaluated.

The problems identified were surface subsidence, surface erosion, leachate and gas. Leachate resulted from water entry into trenches where subsidence occurred. Subsidence was attributed to random placement of waste containers into trenches leaving voids. The poorly compacted cover soil initially bridged the voids and subsequently collapsed and siphoned into the voids. Surface potholes and slumps resulted. Extensive potholing occurred during and after precipitation when the Sheffield loess soil piped into the voids. Long-term soil consolidation also resulted in area settlement. Potholes and slumps along the tops of walls between trenches constructed of fill were attributed to collapse of the walls into voids. Long-term subsidence was predicted as waste containers degraded and collapsed causing further slumps and potholes over a 50 year period. Excessive surface erosion resulted from poor vegetation cover and inadequacy of drainage controls.

Approaches evaluated to stabilize disposal site trenches by compaction included dynamic consolidation, pile driving, surface surcharging, and surface compaction. Stabilization and leachate control by solidification with compaction grouting and chemical grouting were deemed effective but expensive. Accelerated degradation of the wastes by aerobic decomposition of organics and in-situ incineration were found to be less effective. Impervious trench caps were analyzed as a final moisture infiltration and leachate control method after stabilization was achieved. Recommendations for long-term trench maintenance were developed.

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INTRODUCTION

The accepted method for disposing of low-level radioactive wastes (LLRW) in the U.S. has been burial in shallow trenches. Fourteen sites have been or are in use during recent years in the United States for disposal of low-level radioactive waste. These sites have been operated either by the U.S. Department of Energy and its predecessor federal agencies, or by private commercial companies. The low-level radioactive waste disposed into these sites has included wastes from defense and other federal research programs, nuclear power plants, universities, hospitals, military bases and other sources using radioactive materials. The low -level radioactive waste has been disposed in containers or in loose form. The burial methods used for the waste containers have included orderly stacking and random dumping. Orderly stacking was usually done with boxes and rarely with drums. Random dumping was the practice for drums, loose materials, and equipment.

During the initial years of operating the sites no major environmental effects were reported. However, some operating difficulties occurred.[1][2][3] The major initial problems were with subsidence of the trench covers placed over filled trenches. The severity of subsidence problems was effected by the types of trench cover soils, climate, waste placement methods, and cover soil placement methods. Subsidence was observed in disposal sites with different soils, climates, and waste and cover soil placement methods. For example, at the Sheffield, IL disposal facility, subsidences were observed in trenches less than one year after placement of the trench cover soil.[3]

Subsidences have allowed pooling of precipitation and surface runoff with subsequent infiltration into trenches. The infiltrating water has produced leachate which has become contaminated with radionuclides. Radionuclide contaminated leachate and/or groundwater has been detected at the Sheffield,IL,Oak Ridge,TN,West Valley,NY,Hanford,WA, Barnwell,SC,Savannah River,SC,and

Maxey Flats, KY, disposal facilities.[2][3][4] Another potential environmental problem that may result where severe subsidence or cracks in cover soils extend to the wastes is gas emissions. Although no measurements were reported for gas emissions at Sheffield, IL the potential exists. Research on leachate samples has identified the formation of methane gas from biodegradation of the leachate. The gases produced have included tritiated methane and ^{14}C.[4]

A case study was performed of the Sheffield, IL low-level radioactive waste disposal facility to identify causes of subsidence and to evaluate methods to stabilize the facility's trenches.[3] A literature review was performed to identify subsidence and other problems and stabilization methods at other low-level radioactive waste disposal facilities. Prior experience of the authors with solid waste disposal site design, operation, leachate and gas controls, and closure was also applied to the Sheffield facility. The results of this work are the basis of the information presented in this paper.

PROBLEMS IDENTIFIED AT LOW-LEVEL RADIOACTIVE WASTE DISPOSAL FACILITIES

Four types of problems have been identified at existing low-level disposal facilities: surface erosion, subsidence, leachate, and gas. Surface erosion and subsidence interact to produce leachate.

Surface Erosion

Surface erosion was found to be extensive at the Sheffield, IL disposal facility. An example of surface erosion is shown in Figure 1. Extensive erosion was due in part to the loess silt type of soil at the facility. Loess is prone to extensive erosion where vegetation ground cover is sparse. Runoff occurs first as sheet flow which gradually develops into poorly defined rills on the trench cover.

Inadequate surface drainage controls and trench cover slopes graded too steeply contributed to the observed erosion rills and gullies. The erosion process can lead to loss of trench cover cap integrity and water infiltration.

Figure 1: Surface Erosion on Trench

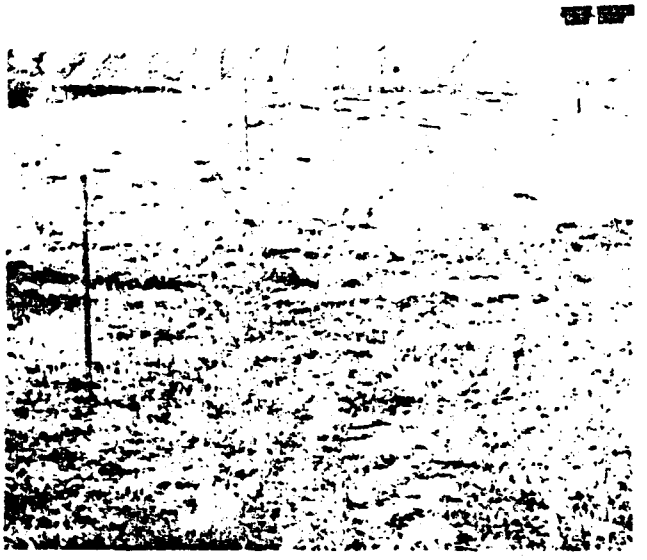


Figure 2: Tire Tracks and Low Spots

Other factors effecting trench surface integrity at the Sheffield facility were areas of potential concentrated infiltration. Areas of concentrated infiltration were maintenance vehicle tracks and low spots which developed between the trenches. An example of vehicle tracks and low spots is given on Figure 2. The tire tracks and low spots are points of accumulation of precipitation and runoff that can allow water infiltration into the trenches.

Types of Subsidence

Three types of trench subsidence were identified at the Sheffield facility: slumps, potholes, and settlement. Potholes were denoted as localized small diameter subsidences with steep irregular walls. Slumps were classified as larger local depressions with sloping sides. Settlement denoted a subsidence occurring over a large area or the entire trench surface. Each type of subsidence was attributed to different mechanisms occurring in the trenches.

At Sheffield, the diameter of subsidences was recorded and the number of occurrences of each diameter was counted. The data are shown in Figure 3. The majority of subsidences were 2 meters (6 feet) or less in diameter. The most frequent size was 1 meter (3 feet).

The age of trenches when subsidences occurred during a two-year monitoring period (October 1978 to October 1980) varied from less than one year to 12 years. The subsidences by trench age are listed on Table 1. Since the Sheffield monitoring period was only two years, the Table 1 data gives only an indication of subsidence occurrences by trench age since not all trenches were monitored at each year of their age.

Mechanisms of Subsidence. Subsidence at Sheffield was attributed to four mechanisms:

1. Potholing and slumping of the trench soil cover caused by the filtering of fine soil particles into the voids and interstices in the backfill soils and around the waste containers.

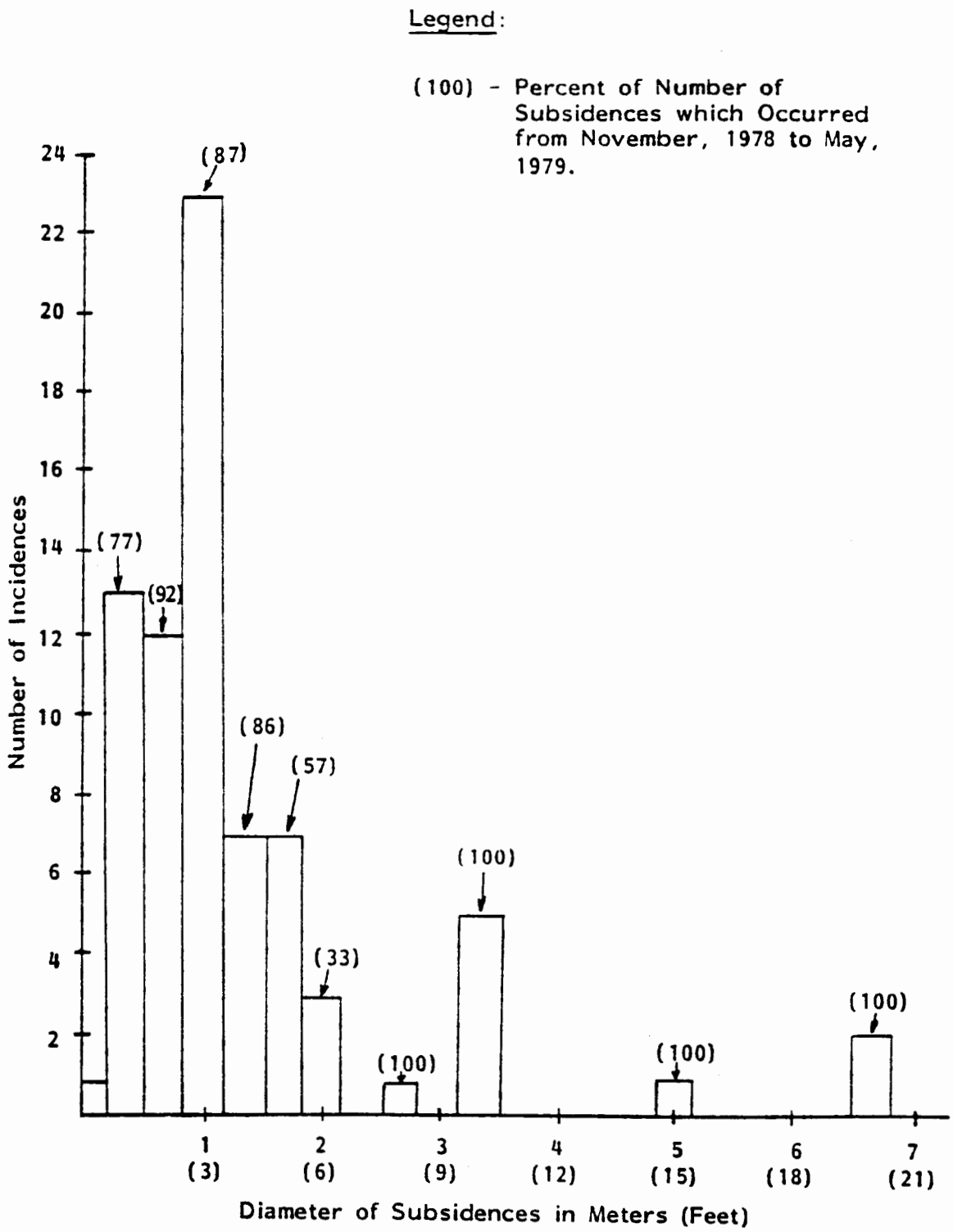


Figure 3 - Subsidence Size Distribution

Table 1 - Subsidence by Age of Trench[3]

Years Since Trench Completion	Number of Subsidences	Number of Trenches Involved	Number of Trenches of Given Age(a) During the Two-Year Period of Monitoring[b]
0-1	14	1	1
1-2	2	2	3
2-3	23	5	7
3-4	7	3	12
4-5	25	5	12
5-6	4	3	10
6-7	--	--	6
7-8	1	1	4
8-9	1	1	2
9-10	--	--	1
10-11	1	1	1
11-12	1	1	1
12-13	--	--	1

[a]Age was calculated from the date of trench completion to the month when subsidences were recorded. Subsidence was recorded during the period from October 1978 through October 1980.

[b]Based on a total of 21 trenches during each time period.

2. Potholes and slumps caused by structural deterioration and collapse of the waste containers.
3. Settlement due to consolidation of the backfill cover soil in the trenches.
4. Slumping and settlement due to long-term deterioration and disintegration of the buried waste and container materials.

The first mechanism was primarily due to the travel of water through the soil resulting from infiltration of precipitation and run-off through the trench caps. The rate and magnitude of subsidence due to the four mechanisms are determined by the initial degree of compaction of the waste containers and backfill soil in the trenches, the orientation of placement and packing of waste containers, the degree of saturation of the trench cover soil and waste due to water infiltration, and the drainage characteristics of the backfill and cover soil.

Leachate

Leachate resulting from entry of water into trenches at the Sheffield facility occurred by surface infiltration in most trenches, and by groundwater intrustion as well as surface infiltration in one trench. Leachate containing tritium was emerging downstream of the trench from a ravine hillside.

Tritium was found to be the most abundant radionuclide in trench leachate sampled at the Sheffield, IL, Maxey Flats, KY, West Valley, NY, and Barnwell, SC facilities. Dissolved species of 90 Sr, 90 Sr, $^{(238,239,240)}$ Pu and ^{137}Cs were found in leachates at these four sites.[4] Other leachate studies have found additional radionuclides of ^{14}C, ^{3}H, ^{60}CO, and ^{241}Am at Maxey Flats and West Valley.[5]

Gas

Biodegradation of organic materials in land burial sites produces methane gas as a byproduct. The rate of gas generation is a function of moisture content, organic content, types of organic materials, temperature, and soil acidity. Entry of water into trenches can provide a moisture content more conducive to methane generation than would occur in a dry trench. Exposed wastes were observed at the

Sheffield facility in three trenches during the two year monitoring period. The exposures were a result of potholing. Exposure of wastes provides a ready pathway for gas emissions into the atmosphere.

Research was performed by Clinton and others on production of gas from samples of leachate taken at the Maxey Flats, West Valley, Sheffield and Barnwell facilities. Methane bacteria were identified in the leachate and were found to produce tritiated methane (CH_3T), tritiated hydrocarbons (HTO and HT), and carbon 14 carriers ($^{14}CH_3$, $^{14}CO_2$). Methane and carbon dioxide are the major byproducts of methane bacteria in landfills.[4]

DISPOSAL FACILITY CONDITIONS CAUSING TRENCH INSTABILITY

Conditions at the Sheffield disposal facility which caused the trench problems were determined to be the following: waste materials, and containers, methods of placing the waste in trenches, trench construction, type of cover soil, placement of trench soil cover, and trench surface maintenance. Problems at other low-level radioactive waste disposal sites may have similar or additional causes.

Trench Construction

Trenches constructed using fill as the trench wall may be subject to collapse. Collapse can occur if the soils become saturated with water. At Sheffield the loess soils were collapsible and lost their strength when wet. Walls of two trenches were constructed of fill compacted to 90 percent (modified Proctor test) layed directly over the natural loess surface soil. These walls experienced 12 subsidences. The subsidences were attributed to failure of the natural loess beneath the fill sidewalls which removed support from the compacted fill. The direction of failure was probably into the trenches on both sides of the trench wall. These subsidences and wall failures occurred after heavy rains. Loess by nature is a uniformly fine grained deposit with a high void ratio and possibly a slight cementation in its natural deposit. The concentration is destroyed when the loess is disturbed or partially to fully saturated. Infiltration of water along the trench walls which were low points for drainage appeared to allow water infiltration into the loess during the rainfall.[3]

Other disposal sites with different types of soils may not experience the same type of failure mechanism.

Placement of Wastes

Two methods have been used to place wastes into trenches at low-level radioactive waste disposal facilities: random dumping and orderly stacking. A schematic illustration of the random dumping of containers is given in Figure 4.[3] Random placement leaves large voids between containers that are bridged by backfill soils and into which cover soil can pipe when the bridges collapse. When containers are uniformly stacked the void space is greatly reduced. Placement of unpackaged loose wastes can produce slumps due to bridging in the waste materials. Due to the potential for contamination of operating personnel and equipment it has not been the practice to compact the wastes directly.

Unpackaged wastes may have an in-situ density, at the time of placement, of as little as 1.4 kg/cu m (150 lb/cu yd) when not compacted. Placement of soil cover or other backfill will create a surcharge on the unpackaged wastes and cause an initial volume reduction (increase in density). The major compaction will be in the form of long-term consolidation. Saturation of the wastes with water will initially accelerate the consolidation process. Uncompacted organic loose wastes may experience a consolidation of 50 percent or more by volume over a long period of time (up to 20 years) based upon settlement experienced in solid waste disposal sites.

Placement of Trench Cover Soil

Backfilling of trenches at Sheffield and other sites was done by pushing soil into the trenches on top of the waste containers. The initial layers of soil cover were not compacted, thus soil bridging occurred over voids between containers. When the final cover soil layers were compacted near the cover surface the compaction pressure did not reach deep enough in the trenches to compact the deeper layers of soil, to collapse the bridging, nor to force soil into voids.

The rapid decrease in vertical pressure in soils by depth when compacted by tracked and rubber wheeled compaction vehicles is

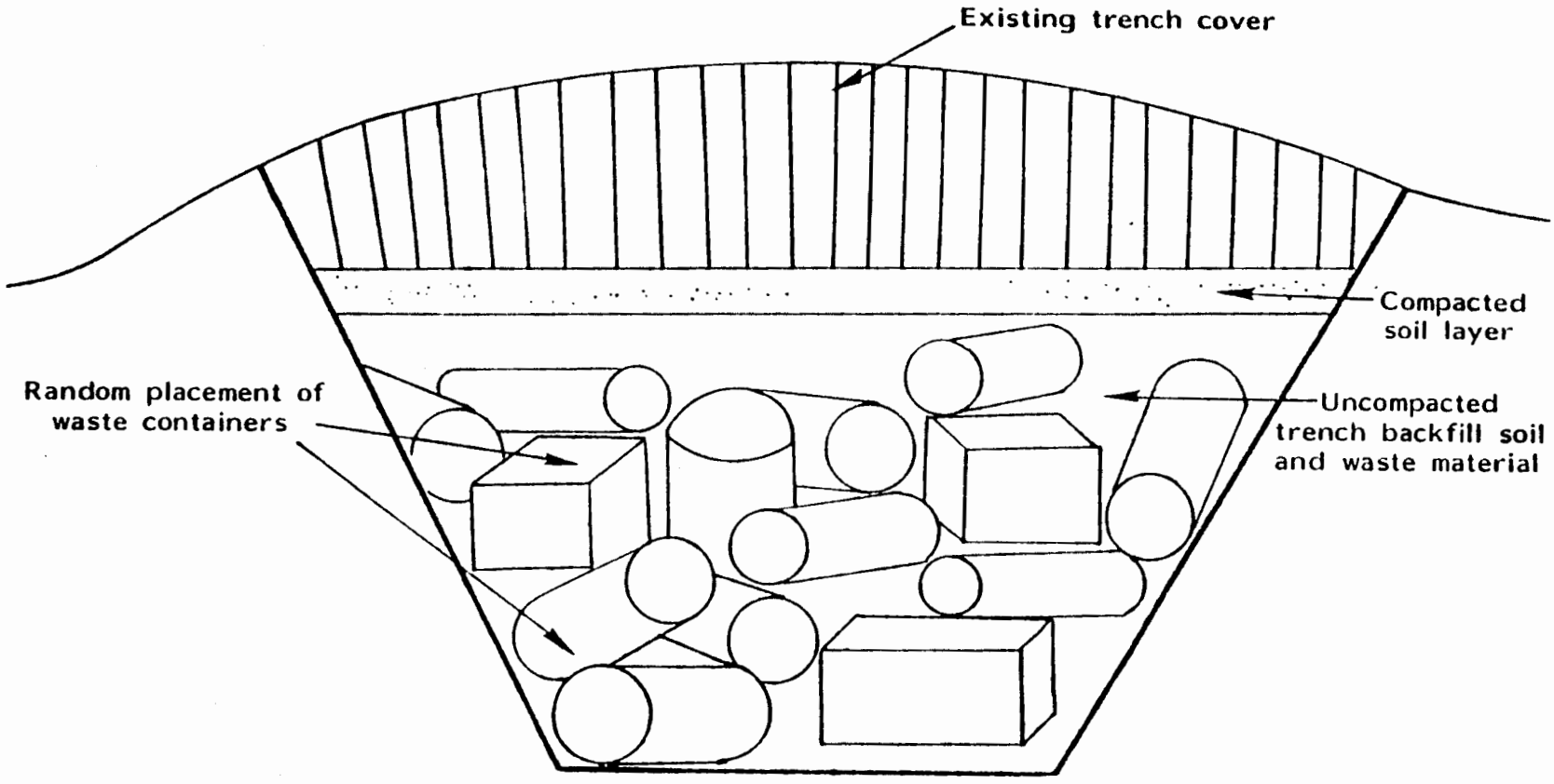


Figure 4 - Schematic Illustration of Random Placement of Waste Containers

shown in Figures 5 and 6.[6] Note that the compaction forces diminish rapidly at depths over 0.6 meters (2 feet) below the vehicle contact point. The poor compaction of trench cover soil was a major contributing factor to trench subsidence problems at the Sheffield facility.

A second factor was the loess soils. The loess is a fine particle soil whose particles filtered into the voids between and beneath the waste containers when soil bridges between containers collapsed. When saturated with moisture, the potential for the loess to pipe into the void spaces increases. The piping extends to the soil cover and creates seepage channels and concentrated infiltration of water. These phenomena produced most of the potholes and sudden slumps at the Sheffield facility.

Waste Materials and Containers

Subsidence from deterioration of waste containers and waste materials will produce sudden slumps, potholes and area settlement. Cardboard containers may collapse when saturated with water and from soil cover surcharging which can occur soon after placement. Some of the slumps and potholes at the Sheffield trenches were attributed to early collapse of cardboard containers. Plywood containers will deteriorate slowly by biodegradation and may take over 10 years to degrade to the point where they collapse. Steel drums will deteriorate by corrosion. The rate of corrosion will depend on the drum material wall thickness and surface protection, and the soil temperature, pH, oxygen level, electrical resistivity, and moisture content. Analyses completed by Stone predict that corrosion pit penetration of steel drums could occur as soon as 10 years or as late as 20 years.[3] The volume of voids from collapsing containers will depend upon the bulk of the wastes inside the container. For all three container materials the load from cover soil and the other wastes will effect the time of container collapse. Depending upon the container size and number of containers collapsing at a given time either potholes or larger slumps in the trench cover soil surface can result.

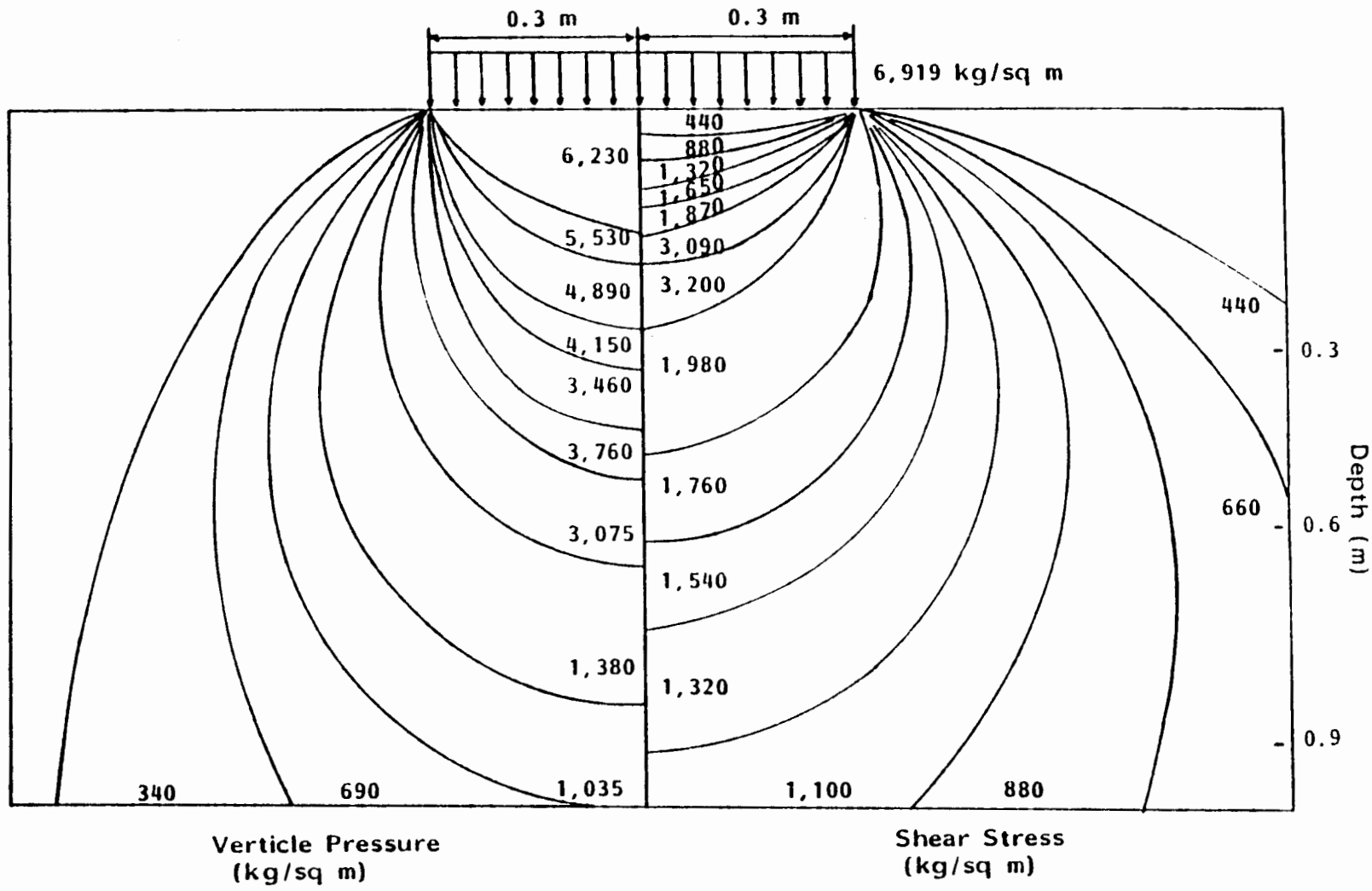
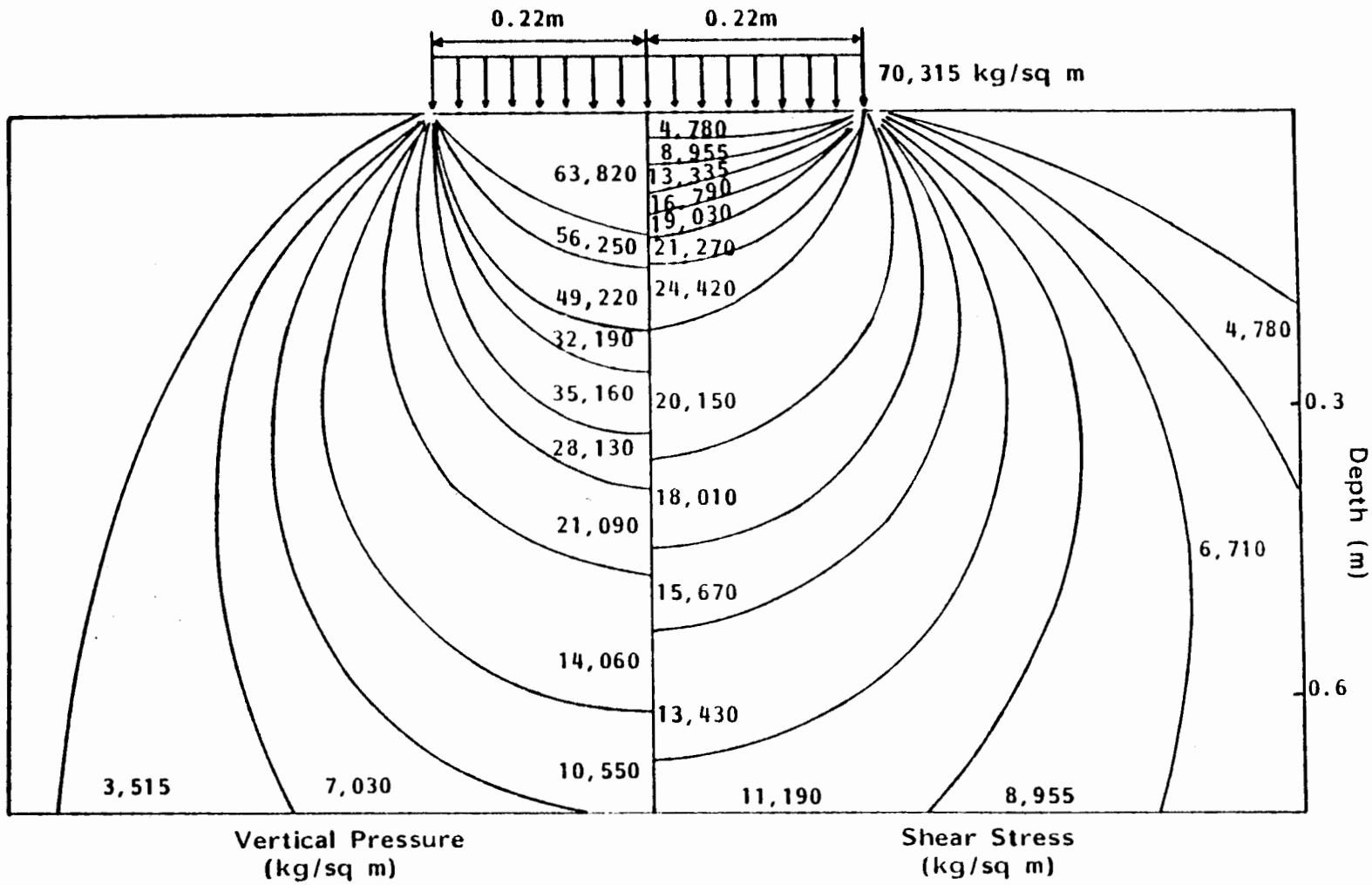


Figure 5: Applied Pressure Distribution Caterpillar D-9 Tracked



Note: Rubber tires inflated to 100 psi

Figure 6: Applied Pressure Distribution-FWD Wagner SF-17 Rubber Tires

Long-term area settlement of trench soil cover will occur from biodegradation of organic waste materials and corrosion of metals. As the materials (including container materials) deteriorate their volume decreases by consolidation and structural disintegration. The same mechanisms described for container collapse will occur over the long-term for the materials. A gradual settlement of the trench surface will result that will vary over the trench surface area (differential settlement) depending upon the distribution of the waste mass in the trench. The area settlement will occur at a slow rate for as long as 50 or more years depending on site climate.

Trench Surface Maintenance

Erosion of trench cover surfaces and damage to cover surfaces by vehicle tracks created rills, gullies and ruts for localized collection and infiltration of water at the Sheffield facility. The freezing and thawing cycles created cracks in the soil surface. Also, where the trench cover and site surface soils are clayey, and expansive, they can crack after prolonged dry periods. The cracks provided points of entry for water into the trenches. All of these conditions were observed at the Sheffield facility as contributing to potholing and sudden slumps from localized water infiltration.

Saturation of trench soil cover over large areas from infiltration can also result in consolidation settlement of uncompacted soils.

Lack of a suitable trench cover vegetation growth contributed to the surface erosion at the Sheffield facility. Erosion rills and gullies were more prevalent where vegetation was sparse or non-existent.

DISPOSAL SITE STABILIZATION MEASURES

Approaches to stabilizing low-level radioactive waste disposal sites to mitigate the described problems were evaluated for the Sheffield site. The stabilization approaches evaluated are also applicable to other low-level radioactive wastes disposal facilities. The approaches cover subsidence stabilization, gas and leachate control, and surface erosion control.

Trench. Stabilization Techniques

Stabilization of the facility is the major approach that was evaluated for the Sheffield facility. Leachate and gas emission problems can be partly controlled by trench stabilization. Stabilization refers to minimizing potholing, slumps, and settlement of in-place trench soils or wastes by remedial compaction or by structural stabilization using grouting techniques.

Compaction Techniques. Five compaction techniques were evaluated: dynamic consolidation, pile drivers and compaction piles, surcharging, blasting impact, and shallow compaction. The advantages and disadvantages of each technique are described below.

Dynamic Consolidation. Dynamic consolidation was developed for deep compaction in Europe.[7] Heavy weights of 5 to 40 tons are dropped onto the test cells from heights of 20 to 100 feet according to a predetermined pattern developed for each trench. Dynamic consolidation has been shown to be effective to depths of 50 feet with surface settlements of 5 to 15 percent of the total fill thickness being achieved.[7] A high capacity crane lifts the weight, which is dropped several times at each selected location. After completing passes over the entire site, subsequent passes are completed at selected time intervals which may be up to three weeks apart. The timing depends on the type of soil.

The high energy impact from the falling weight is believed to cause partial liquefaction of granular and non-saturated soils thereby allowing the soil mass to settle into a dense state. In fine-grained soils the consolidation mechanism is not as well understood. It has been hypothesized that in saturated cohesive soils the shock waves and high stresses from the weight impacts cause gradual liquefaction and consolidation of the soil mass. Tension cracks found around the impact points increase the permeability of the soil mass and allow percolation of existing pore water.[7]

The trenches at Sheffield and many other low-level radioactive waste disposal facilities are less than 50 feet deep so that the dynamic compaction could collapse the waste containers if desired.

However, if waste containers are collapsed the potential for release of radioactive gas is increased. The contaminated wastes would also be exposed to percolating water which could pick up and transport radionuclides. The potential exists for radioactive contamination of the tamping weight and personnel. To avoid the potential emissions that could result from dynamic consolidation, the tamping weight and dropping height should be selected to have an effective depth no greater than the depth of the soil cover. The impact force would then be sufficient to collapse soil bridges over voids between containers and force cover soil into the upper voids.

Use of dynamic compaction on trenches at the Sheffield facility was projected to require up to an additional 1.8 meters (6 feet) of cover soil to fill the voids if waste containers were collapsed. About 0.3 meters (1 foot) of additional soil may be required if only the cover soil was compacted with some soil movement into voids between containers without collapsing the waste containers.

Pile Drivers and Compaction Piles. Pile driving is most suitable for densification of loose cohesionless soils although partly saturated clayey soils and loess have also been successfully compacted.[7] Densification occurs from two effects: displacement of material equal to the volume of the pile, and the vibratory effect in the driving of the pile.

The pile driving method consists of driving wooden piles, at close centers on a predetermined grid pattern, into the trenches. The compaction pile approach consists of driving a hollow steel mandrel with a detachable bottom to the required depth, filling the mandrel with cohesionless material or concrete, withdrawing the mandrel, and leaving the column of cohesionless material or concrete in the hole.

The pile penetration to the bottom of trenches and vibratory effects may collapse soil bridges, start soils to flow into voids, collapse waste containers, and puncture containers.

If waste containers are punctured or collapsed by the driven pile, the pile (or mandrell) may become contaminated by radioactive

materials. Venting of radioactive gas is also possible when the pile is withdrawn. Any contaminated piles or mandrels could be left in the trench for final disposal after completion of the pile compaction. Care must be taken not to penetrate any drainage system beneath the trench to avoid potential release of leachate with radionuclides.

Puncturing and collapsing of waste containers as well as protection of trench drainage systems can be accomplished by only driving piles to the depth of the cover soil. Soil bridging over voids between waste containers may be collapsed by the vibrations during driving of the piles. Compaction piles would be more effective since they would maintain a greater compaction pressure than when driven piles are withdrawn.

Surcharging. When foundation loads are applied to cohesive soils volumetric strain is induced which increases pore water pressure.[8] As sufficient time elapses, water flows out of the soil pores, accompanied by dissipation of the excess pore pressure and resulting in consolidation settlement. Application of a surcharge load can eliminate most or all of the primary consolidation and resulting settlement. Surcharging is most applicable to soft clays, silts and organic deposits.[7] The maximum effective treatment depth is variable and depends on the type of soil, surcharge load intensity and surcharging period. The surcharging period and load intensity will depend upon the coefficient of consolidation of the soil, degree of saturation, and the drainage path.

Surcharging of trenches can be done by placing mounds of soils or other materials on the trenches. Soil, construction debris or other surcharge material may have to be imported. Placement of differential settlement markers or piezometers could be used to monitor the consolidation, predict load intensities, and determine the most effective load period.

The surcharging technique will not puncture containers nor damage any drainage system. Some containers may collapse. Release of radioactive gases and leachate would be minimum. Thus, exposure of workers and equipment to radioactivity would not likely occur.

Blasting. The technique of blasting using explosives can be applied to deep compaction of saturated and partly saturated sands and saturated silts.[7] The blasting compaction procedure consists of:

driving several pipes to the desired depth (usually two-thirds the thickness of the stratum to be compacted); lowering explosives to the bottom of the pipes; withdrawing the pipes; backfilling the holes; and detonating the explosives in a pre-determined pattern. The shock waves and vibrations generated by sequential detonations may cause localized spontaneous liquefaction within the soil mass, with the subsequent expulsion of pore water. Displacement, remolding, and densification of the soil mass then follows.

At Sheffield and other low-level radioactive waste disposal facilities the shock waves may collapse containers and deep voids, as well as soil bridges. Vibrations may cause soil to pipe into voids. Applicability of the technique to unsaturated silty fine-grained trench soil cover, such as the loess at Sheffield, will be limited.

If the pipes are only driven into the trench cover soil there is minimal likelihood of contamination of the pipe. The explosives placement holes would have to be properly backfilled to avoid venting release of radioactive gases after detonation. The technique requires strict controls and expert personnel to properly size and position the explosive charges.

Grouting Techniques. Grouting can be used for compaction of trench cover soil as well as solidification of the cover soil and encapsulation of waste materials.

Compaction Grouting. The method consists of extruding highly viscous soil cement grout into the voids of a compressible soil mass. The injected grout remains as a homogenous mass that expands as injection continues and exerts a radial compressive force on the surrounding soil. The radial compressive force compacts the soil in place. The grout usually consists of a cement-sandy loam mixture. Clay content is minimized to avoid shrinkage. The grout may be injected either from the bottom up or the top down.

If the grout is injected at the bottom of the trench, waste containers may be penetrated. A more feasible approach would be to inject the grout to a depth just above the containers near the bottom of the trench soil cover. Grout could then flow into voids

between the top layer of containers and form a solid seal to prevent future soil piping into voids. The soil cover would be stabilized by the compaction force. By injecting above the waste, the potential for contamination of injection equipment would be minimized.

Solidification Grouting. Low viscosity chemical binders are used to permeate through fine soil pores and solidify to produce an impermeable mass. Very low viscosity chemicals such as Acrylamide can penetrate into silt and loess such as at the Sheffield facility. Other higher viscosity chemical,cement,and other grouts are available for different soil and waste conditions. The solidification grout is injected into the soil cover at selected locations to achieve penetration throughout the cover. The grout solidifies in-place. Polymers, such as Acrylamide which was considered applicable to the Sheffield facility, solidify into stiff gels. Some grout materials are subject to deterioration in acidic or alkaline environments which will require selection of a grout for specific sites.

One approach that can be used is to first inject a higher viscosity, less expensive soil cement grout into the void spaces between the waste containers. Then a low viscosity chemical grout could be injected into the soil cover. This approach would minimize cost and provide solidification stabilization of both the soil cover and wastes.

If only the soil cover is solidified, it will form permanent bridges over voids between the waste containers. If the void spaces between waste containers are filled with grout leachate will be minimized and soil piping into voids will be eliminated.

Biological Technique. A biological technique for accelerating stabilization of organic wastes in-situ was developed and field tested by Stone at a landfill in Santa Clara,CA.[9] Air was injected into trenches containing buried solid waste to increase the biological (aerobic) decomposition rate. The results indicated that a 25 percent volume reduction in the solid wastes could be achieved in about 90 days. Air injection through wells inserted to the top of the buried waste containers would be feasible. However, for maximum effectiveness the containers would have to allow air to enter.

This would require collapsing or otherwise breaking open the containers. Aerobic stabilization could stabilize the organic portion of the wastes and minimize long-term subsidence. At the Sheffield facility the waste content in the trenches varied from 33 to 60 percent of the total trench volume. Given a generally low organic content and waste container packaging, accelerated biological stabilization has a low feasibility for some trenches. In trenches where the organic content of the waste is high and where wastes were not in containers the method would be feasible.

In-Situ Combustion. Destruction of the organic portion of the buried wastes may be accomplished by in-place incineration. Two general techniques exist: gas injection and air injection.

Gas Injection Combustion. The gas injection method was described by Phillips [10] in a U.S. DOE report. Gas and air injection wells would be inserted into the wastes in a selected pattern with the gas acting as the fuel. The gas would be ignited and the resulting flame would ignite the wastes.

It would be necessary to maintain high temperatures for sufficient time to pyrolize wastes inside drums if they are also to be destroyed. Problems could occur with uneven combustion, localized flame fronts, and isolation of wastes from the flame by intermixed backfill soil or buried equipment. It is also possible for a rapidly burning mass of waste to collapse quickly and produce a pothole in the soil cover where combustion gases containing radionuclides could escape. Once the wastes are incinerated, the ash residue will contain the radionuclides in a concentrated form that may be more easily leached out by percolaing water. Experience with solid waste landfill fires show them to be difficult to control and areas of the landfill surface may collapse releasing smoke and gases to the atmosphere.

Air Injection. Air injection through the soil cover just above the wastes and ignition by electric spark,gas burners,or hot charcoal dropped down wells is an alternative to gas injection. It would be necessary to place a temporary cover over the trench surface to force the air downward into the wastes. However, since the wastes are in

containers and the organic content is low, the combustion may not be complete. Stone developed, designed, and field tested this method on municipal solid wastes. The combustion rate was about 30 days in each of two test cells. A burnout of about 95 percent of the organic content was achieved with an 85 percent reduction in waste volume (some inerts were present). Due to the slow uniform combustion rate achieved the cover soil did not collapse differentially and allow smoke and gases to vent.[11]

Leachate Control

Leachate containing radionuclides has been found at Sheffield, Oak Ridge, Maxey Flats and West Valley low-level radioactive waste disposal facilities. Leachate may be controlled by controlling surface water and groundwater infiltration into the burial trenches. Some sites have trenches that were constructed where groundwater flooding occurred. One trench at the Sheffield facility experienced groundwater infiltration. The "bathtub" effect has also been observed where the rate of infiltration of surface water into a trench is greater than the rate of discharge out of a trench. Leachate may be controlled in existing trenches by preventing water from entering a trench, encapsulating the waste materials, or by providing leachate collection and treatment facilities. In new trenches, the bottoms and side walls can be lined with clay, synthetic membranes or other soil treatment chemicals to prevent groundwater infiltration.

Impervious Caps. A method that has received extensive study has been the use of impervious caps over completed trenches. Caps of clay, steel reinforced concrete, asphalt, and synthetic membranes were evaluated for the Sheffield facility.[3] The structural capabilities of the various cap materials was reviewed for their ability to maintain structural integrity when subsidence occurred. Without stabilization of the trenches at Sheffield the majority of subsidences were from 0.3 to 2 meters (1 to 6 feet) in diameter. (See Figure 3). The largest subsidence was 6 meters (20 feet) in diameter. After stabilization of the trenches the subsidences would be smaller and shallower. A desirable trench cap would have to remain functional

if subsidence occurred. Periodic monitoring and repair may be necessary for any cap.

Clay caps, when wet, may adjust to small subsidences without losing their low permeability or cracking. However, to avoid pooling of surface water if subsidence occurs, they may require periodic regrading.

Synthetic membrane liners can adjust to minor subsidences. They can be used as a primary or secondary barrier to surface water infiltration. The effects of exposure to radiation on the liner structural integrity may have to be considered.

Use of steel reinforced waterproofed concrete for trench caps is technically feasible. Proper structural design would protect against collapse if subsidence occurred. However, concrete would be a very expensive method due to the large quantities required.

Asphalt trench caps would present problems if subsidence occurred. Asphalt membranes and sprayed asphalt are two options. Asphalt caps could crack if subsidence was significant.

Wick Effect. The use of a convex arched clay trench cap placed over gravel and extending beyond the sides of the trench has been proposed to serve as a wick. The strong capillary action of the clay and the weak capillary action between the clay and gravel would cause water to remain in the clay. The water would then move by capillary action and gravity laterally downward to the edge of the clay cap extending beyond the outside edges of the trenches. The water would then enter drains or clay slurry walls could be installed to further wick the water below the trench bottom. A secondary synthetic membrane or clay arched cap could be installed below the gravel layer to provide a secondary water seal. The wick effect might be short-circuited by subsidence if a low point occurred over the trench. Water could then collect in the subsidence surface depression and emerge on the bottom of the subsidence depression at the low point of the clay cap. The water may then accumulate and drain into the gravel if the capillary force is not sufficient to pull the water angularly up the sides of the depression in the clay cap.

The method requires field testing to verify the basic concept and the effects of subsidence depressions on the wicking mechanism.

Encapsulation. Encapsulation of the wastes by impervious materials would prevent leachate. The solidification grouting techniques previously described would apply. With the wastes encapsulated, they would be sealed from contact with water.

Leachate Collection and Treatment. An alternative used at solid waste disposal sites that would apply to some existing and to new trenches is leachate collection and treatment. An impervious trench liner, leachate collection sump and leachate pump would be installed in new trenches to collect the leachate. In existing trenches with leachate sumps the leachate could be pumped out. Leachate treatment by chemical and filtration methods would remove contamination.

Gas Control

Control of radioactive gas emissions will require maintenance of trench covers to prevent escape of gases, and minimization of water infiltration to reduce gas production from biological degradation of the organic portion of the wastes. Gas emissions may be controlled by encapsulation of the wastes and/or cover soil, or a gas removal system. Grouting to encapsulate the waste materials would minimize gas production and hinder the escape of gas.

Gas extraction wells can be installed to remove and treat gases produced. Gases can be treated at the site by dessicants and molecular sieves to remove any radionuclides. This method would require extensive long-term site maintenance and operation of the gas control system. Disposal of the dessicants and sieves containing collected radionuclides would also present an additional expense due to the concentration buildup of radionuclides removed from the gases. The effectiveness of radionuclide removal from the gases must be tested.

Surface Erosion Controls

Control of surface erosion can be accomplished by vegetation, proper slopes and installation of drainage facilities. Grading of trench covers results from two factors: to provide a mound over the trench

to compensate for future subsidence; and to provide suitable drainage to avoid pooling of water. The difficulty arises when slopes are too steep or long to maintain proper drainage flowrates. Small drainage benches may be required to intercept running surface water to control the velocity and thus minimize surface erosion. Drainage benches would be located to prevent surface runoff velocities from exceeding the level where erosion could occur for the type of trench cover soil/cap materials and vegetation. An extensive facility drainage system is also necessary to divert other surface runoff away from trenches.

Selection of vegetation is often restricted by climate and soils conditions. The best cover for erosion protection is grassy vegetation. Shallow rooted vegetation is preferred to avoid penetration of impervious caps and wastes.

Prevention of damage to trench surfaces by vehicles has been an initiator of erosion. Vehicles should not traverse trench covers or caps to prevent formation of tire tracks which can be precursors of erosion and provide collection points for water which can infiltrate into the soil cover.

CONCLUSIONS

Past disposal techniques and site designs have created problems with burial trench surface stabilization and leachate at existing low-level radioactive waste disposal facilities. Technically feasible approaches to stabilize completed burial trenches at existing facilities and avoid similar problems in new trenches include the following:

1. Stabilization of trench cover soil by compaction. Compaction by dynamic consolidation, pile drivers and compaction piles, surcharging, and compaction grouting are the most feasible alternatives.
2. Stabilization of waste materials. Accelerated biological degradation and in-situ incineration have the potential to stabilize the wastes and therefore the trenches. Problems may occur with controlling combustion, gas venting and incomplete combustion.

3. Solidification grouting. The wastes and the cover soil can be grouted to solidify the trench materials. The solidified materials would eliminate subsidence and leachate if the proper grout is used.

4. Control of leachate from trenches can result from proper trench stabilization and by specially designed trench caps that prevent water infiltration.

   a. Impervious trench caps of clay or synthetic membranes will control infiltration of water into trenches. The clay and synthetic membrane liners are the most reliable trench caps due to their ability to adjust to moderate subsidences without failure. Concrete was evaluated as too costly.

   b. Wick trench caps to siphon water beyond the edges of trenches by capillary action. Wicks may fail if subsidence occurs, and thus are more feasible on compaction stabilized trenches.

   c. Leachate can be collected from sumps where they exist and treated prior to disposal.

4. Control of landfill gas can be achieved by encapsulation of the wastes and by extraction and treatment of gases. Control of moisture infiltration will reduce the rate of methane gas production.

5. Surface erosion controls to reduce surface water infiltration can be accomplished by proper grading and drainage systems, by selecting vegetation offering good ground cover, and by preventing damage to trench cover soil surfaces from vehicles.

6. Orderly stacking of waste containers to minimize voids, backfilling around waste containers with cohesionless materials (such as sand) to fill voids, and proper compaction of trench cover soil will minimize the potential for subsidence in operating burial trenches.

7. Design of new burial trenches with impervious liners, leachate collection sumps, and impervious caps will prevent leachate problems encountered in existing leachate trenches.

8. Long-term periodic maintenance of trenches will be required to assure the trench surfaces are kept in proper repair, vegetation cover remains intact, and any subsidence is regraded.

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DISCUSSION

M. A. Feraday: In 10 CFR 61.56(B), it says the void spaces within the waste package must be reduced to the extent practicable. In your experience, how much of the subsidence is a result of voids left within containers which will eventually collapse? What is the potential for reducing this by insisting on the packages being filled?

R. L. Kahle: The major cause of the subsidences at Sheffield was due to void spaces between the containers.

M. A. Feraday: What about within the containers?

R. L. Kahle: That would depend. A number of observations indicated some of the covers came off some metal drums when they were dumped. Is that what you mean by within the containers?

M. A. Feraday: No. For example, if you have a 210-L drum which contains only a little package, then most of the space in the drum is empty.

R. L. Kahle: We've used that as coming into play on a longer-term basis or if the container were damaged or collapsed from overburden. Then that volume would compress to the point where the waste provided support to the container. We've used that as a potential for future subsidence. That would be a result of the containers themselves degrading and collapsing.

M. A. Feraday: Do you feel that the people who are sending the waste now are filling in these containers adequately?

R. L. Kahle: Some of the containers apparently were loosely packed. In one situation, containers were built around things such as shelving and other equipment that left a lot of voids.

L. H. Stinton: Have the methods summarized in your paper for trench cover and stabilization been demonstrated in the field to show their effectiveness?

R. L. Kahle: I don't think those methods have been used in the field. There have been some preliminary studies as to their applicability. There are still some questions as to whether the compaction methods I pointed out could be applied without damaging the waste containers.

L. H. Stinton: It seems like some of the logistics could get complicated, and it would be difficult to prove that you have done what you set out to do.

R. L. Kahle: In terms of achieving adequate filling of voids and actual stabilization, yes, that can be a problem. That's why some initial tests would be required.

J. A. Halpern: You mentioned that there were variations between the compacted and uncompacted techniques. Were you able to do an analysis of past records, or were there any records that indicated the amounts of subsidence for those areas where it was compacted versus uncompacted?

R. L. Kahle: No, because the areas where there was compaction were not defined. In other words, the data weren't sufficient to identify those areas.

J. A. Halpern: Did the records indicate the types of materials that may have been used for backfill and the weather at the time, and was it consistent through all the trenches?

R. L. Kahle: Yes. We knew the backfill; it was the excavated material, and it was fairly consistent over the surface of the site, primarily loess with a little clay in it.

T. J. McCartin: With respect to subsidence, is there any significant difference between disposal above the water table and disposal below the water table?

R. L. Kahle: I mentioned a problem that could develop with a fluctuating water table. In that case there would be significant effects. By disposal below the water table do you mean including infiltration of water into the waste mass area?

T. J. McCartin: With respect to the regulation, you can dispose below the water table if diffusion is shown to be the dominant transport mechanism. So it would be below the water table and below the infiltration.

R. L. Kahle: Yes, if there is any appreciable degree of diffusion, two things can occur. If waste materials become saturated with water, although the water didn't move, that would retard some of the biodegradation of some of the organics. When there is too much moisture, the bacteria, which are the major forces, can no longer operate. Moisture may change the corrosion mechanism of some of the metal containers, and those areas, I would foresee, are where the impacts would occur.

C. M. Timm: Roughly, how long does it take for these potholes and sinks to occur? You had some pretty big ones there, and you had to have some evidence that they were going to occur.

The corollary to that is, would the active monitoring and maintenance program in some way reduce their impact because you could fill them before a lot of water moved?

R. L. Kahle: It definitely requires an active maintenance program. However, as you could see, some fairly large holes did develop. At that particular site, once the surface soils get wet, it's very difficult to move the equipment around, and that creates a problem in trying to fill it in while it's in the act of subsiding.

Prediction is a little more difficult because you don't know what's going on at particular points. Holes occurred at random over trench surfaces and along boundaries of trenches.

L. S. Karably: Is it your contention that all of the containers will eventually fail?

R. L. Kahle: Considering what we learned, let's address the metal containers. Many of them were just 55-gal drums with no extensive surface protection to prevent corrosion. They will eventually corrode, particulary under these wet conditions. The other containers will eventually biodegrade. The time period is not as well defined. It depends a lot on the moisture content within the trenches and on corrosion, and to some extent the biodegradation also depends on certain physical-chemical characteristics of the soil.

L. S. Karably: Why would you be concerned, then, in the dynamic compaction scheme about destroying containers that will eventually fail?

R. L. Kahle: At some time in the future when these containers do fail, some of the radioactive materials will have decomposed, so that there would be less radiation inherent in the materials at the time of collapse.

L. L. Karably: Don't you think a more appropriate scenario would be to dynamically compact the site and construct a new cover over the trench, for instance, thus eliminating the groundwater and surface infiltration problem now, rather than prolonging this into a longer open-ended problem?

R. L. Kahle: This was considered. If, in some of these trenches where groundwater was a problem, the volume where wastes were located was encapsulated as well, that would be a viable approach. In other words, since the trench sides and bottoms are not sealed, any water coming in from underground wouldn't penetrate the wastes if they were grouted or encapsulated in some manner. In that respect what you're saying would be true.

through 14, data records in terms of settlement vs time after installation of SP1 lag each other.

As of the beginning of September, the settlement plate data suggest that the Trench No. 4 cap design is superior to that of either Trench No. 1 or Trench No. 2. This is based on the following interpretations of the relative movements of SP1 (bottom), SP2 (middle), and SP3 (top) within a given trench, and the comparative movements of the settlement plates among the three trenches:

1. For each trench, the movements of SP1 and SP2 were approximately the same for the first 200 days. This suggests that arching probably did not take place in any of the trenches at the CGHF Site.

2. In Trench Nos. 1 and 2, the slope of the settlement vs time curve for SP3 closely parallels the slopes of the curves for SP1 and SP2 over a given monitoring interval within the first 200 days. This suggests that the cap is indeed tracking the decaying or consolidating waste. In Trench No. 4, on the other hand, the slope of the SP3 curve is much shallower than the slopes of either of the other two curves, indicating a much lower rate of settlement. In fact, the rate of settlement near the surface of Trench No. 4, as indicated by SP3 (refer to Fig. 14), seems to be approaching zero, whereas the rate of settlement of the materials below the soil beam, as indicated by SP1 and SP2, appears to be increasing.

3. In terms of magnitude of surface settlement expressed as a percentage of waste settlement, Trench No. 4 (40%) is clearly outperforming both Trench No. 1 (73%) and Trench No. 2 (54%).

4. After approximately 200 days, SP3 in Trench No. 1 and Trench No. 2 exhibited a substantial increase in settlement rate. This occurred at a time approximately coincident with Tucson's "monsoon" season when short-term, locally heavy rainfalls are common. A number of such thundershowers were observed to occur at the CGHF Site shortly before and during the last monitoring period. Therefore, the increase in settlement rate for that period (200- 250 days) is attributed to the deleterious effect of moisture on the shear strength of the near surface soils that comprise the Trench No. 1 and Trench No. 2 caps. The fact that only SP3 in Trench Nos. 1 and 2 exhibited an increased rate of settlement (i.e., increased slope of curve) for that period suggests that excessive moisture had not infiltrated the cap deeply enough to affect the strength of soils at greater depths.

Data are not presented for Trench No. 3 because, although the cap design is basically the same as that of Trench No. 4, the extreme loading conditions and certain characteristics of the as-built structure at the time of the test resulted in complete collapse of the cap-crown system.

ML Site

The trenches at the ML Site were completed at various times, starting with Trench No. 1 (3 April 1982), then Trench No. 4 (20 May 1982) and finishing with Trench No. 2a (28 June 1982). Figures 15 through 17 present the limited

STRUCTURAL MONITORING PLAN

CGHF Site

Settlement plates were installed at three elevations in each of the trenches at the CGHF Site. The plates are located as follows: one plate (SP1) on the top of the simulated waste in order to monitor decay rates; one plate (SP2) approximately midway in the cap; and one plate (SP3) at the top of the cap below the crown. The latter two settlement plates are used to measure relative movements within the cap itself so that evidence of soil arching can be detected. If monitoring indicates the following sequence: SP1 settlement $\geq$ SP2 settlement > SP3 settlement, then soil arching is occurring. If, on the other hand, the magnitude of settlement for all plates is the same, then no arching is occurring and the cap and crown are sliding past the trench sidewalls and following the decaying wastes. In trenches having a soil beam, settlement plates 2 and 3 were placed immediately below and above the soil beam, respectively.

ML Site

Experience with structural monitoring at the CGHF Site suggested that settlement plates were not needed at three different elevations in order to monitor movement of the waste-cap-crown system adequately. The surface elevation of the trench (top of crown) could be used in lieu of SP3. For this reason, and because the trenches at the ML Site were not crowned, only two elevations within each trench at the ML Site were monitored: the top of the simulated waste, and either approximately midway in the cap (Trench No. 1) or immediately below the bottom layer of geotextile (Trench Nos. 2a, 3, and 4). Another feature of the structural monitoring system at the ML Site is that, with the exception of Trench No. 1, two settlement plates were installed at each of the two elevations, one at each end of the trench along the longitudinal centerline. This was done for two reasons: first, to determine if there were any differential settlements taking place at a given elevation within the trench, and, second, to avoid penetrating the geotextile.

It should be noted that prior to backfilling above a given settlement plate elevation, a section of PVC pipe was placed over the settlement plate extension rod to prevent frictional downdrag on the rod should differential settlement of the cap occur.

A system of hydrologic monitoring devices (porous cup samplers) was also installed within and around the trenches at both the CGHF and ML Sites. A discussion of the hydrologic monitoring plan is outside the scope of this paper.

RESULTS AND ANALYSIS

CGHF Site

The trenches at the CGHF Site were completed (crowned) in early February 1982. Monitoring, however, had been ongoing since the dates of installation of settlement plates in the individual trenches. Therefore, as shown in Figs. 12

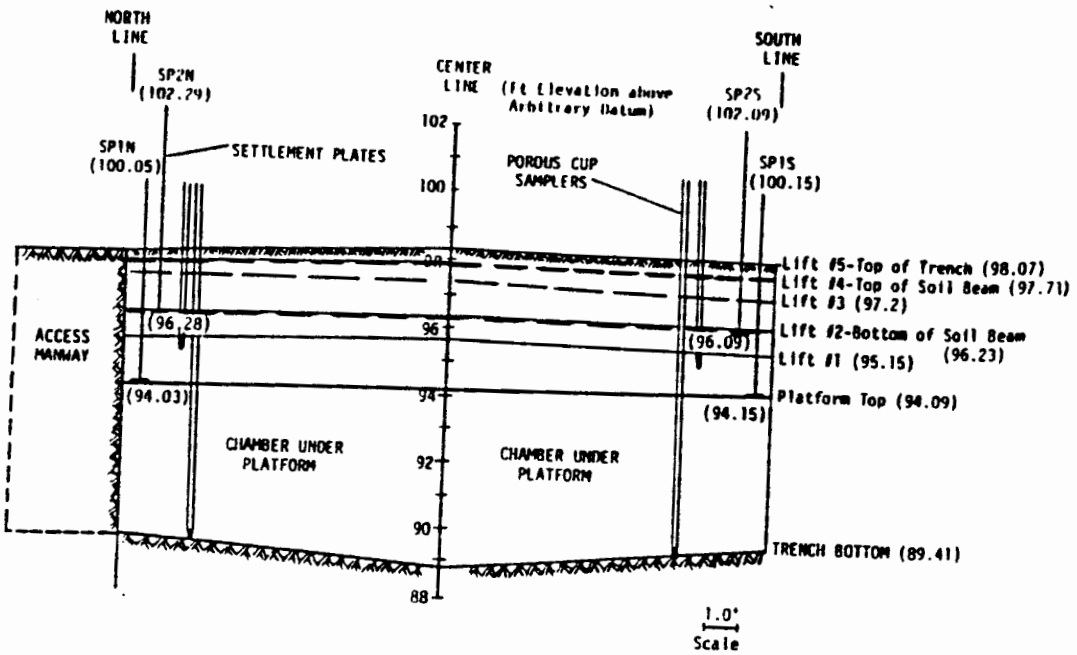


Fig. 10 - Trench No. 3 - Longitudinal Cross Section of As-Built Configuration at ML Site

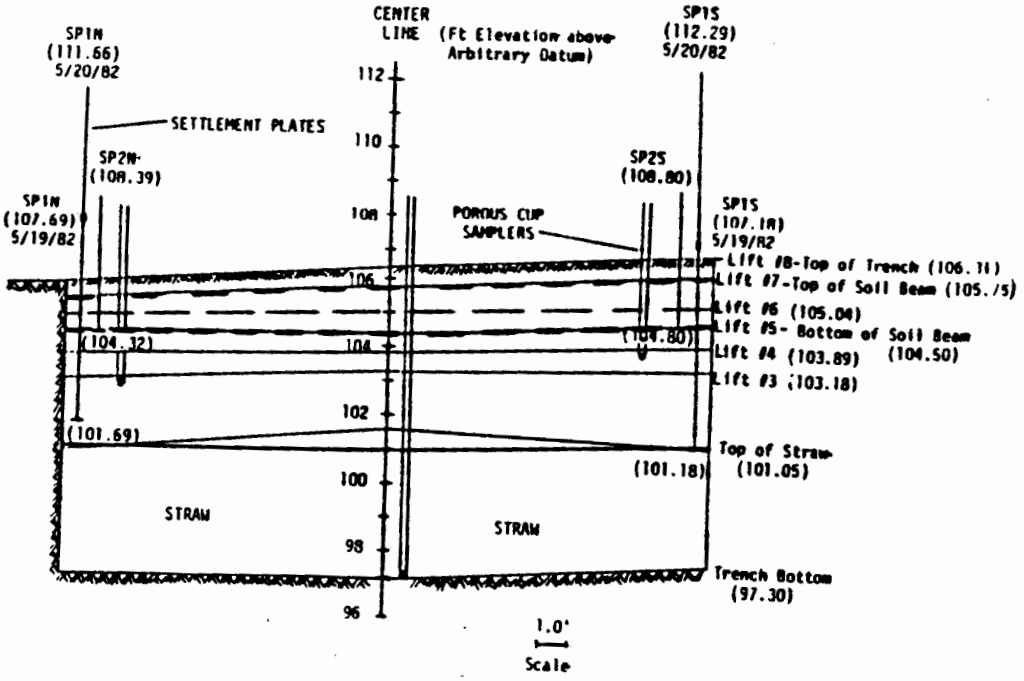


Fig. 11 - Trench No. 4 - Longitudinal Cross Section of As-Built Configuration at ML Site

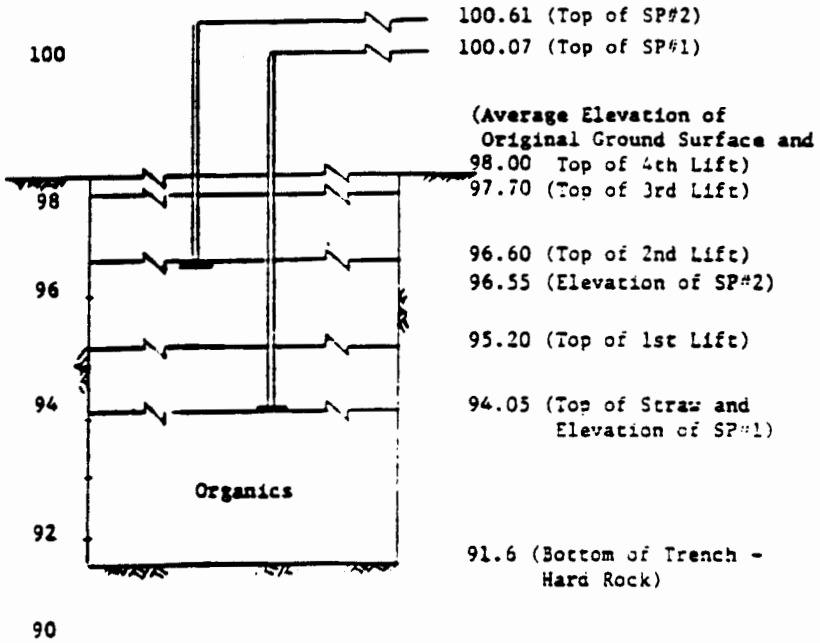


Fig. 8 - Trench No. 1 - Transverse Cross Section of As-Built Configuration at ML Site

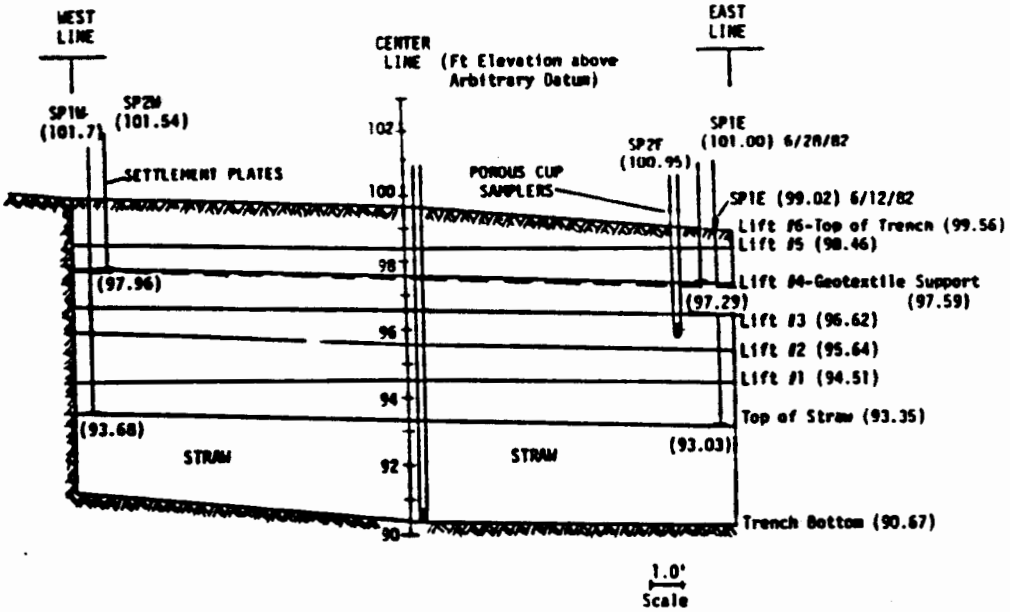
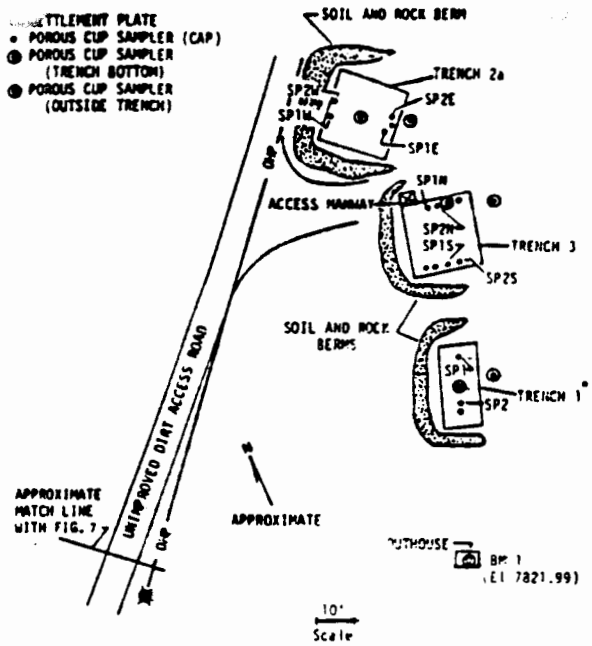


Fig. 9 - Trench No. 2a - Longitudinal Cross Section of As-Built Configuration at ML Site



* Trench No. 1 appears smaller than the other trenches in a top view in that it has no mirafi and hence a smaller crown.

Fig. 6 - Trench Location Plan at NE (Lower) Portion of ML Site

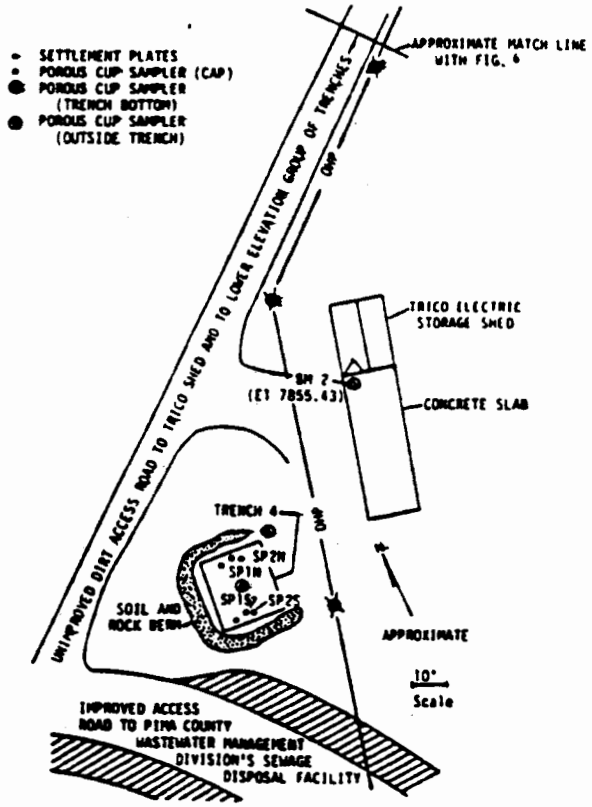


Fig. 7 - Trench Location Plan at SW (Upper) Portion of ML Site

the trench itself. A simple surface runoff collection/drainage system was constructed as shown in Fig. 5. Compaction of backfill for caps and crowns was accomplished by "WACKERS". The degree of compaction and the compaction moisture content were controlled and held to at least 90% of the maximum dry density (Standard AASHTO) and ±4% of optimum moisture content, respectively. Table 2 contains a summary of the pertinent laboratory test data for the CGHF Site soils.

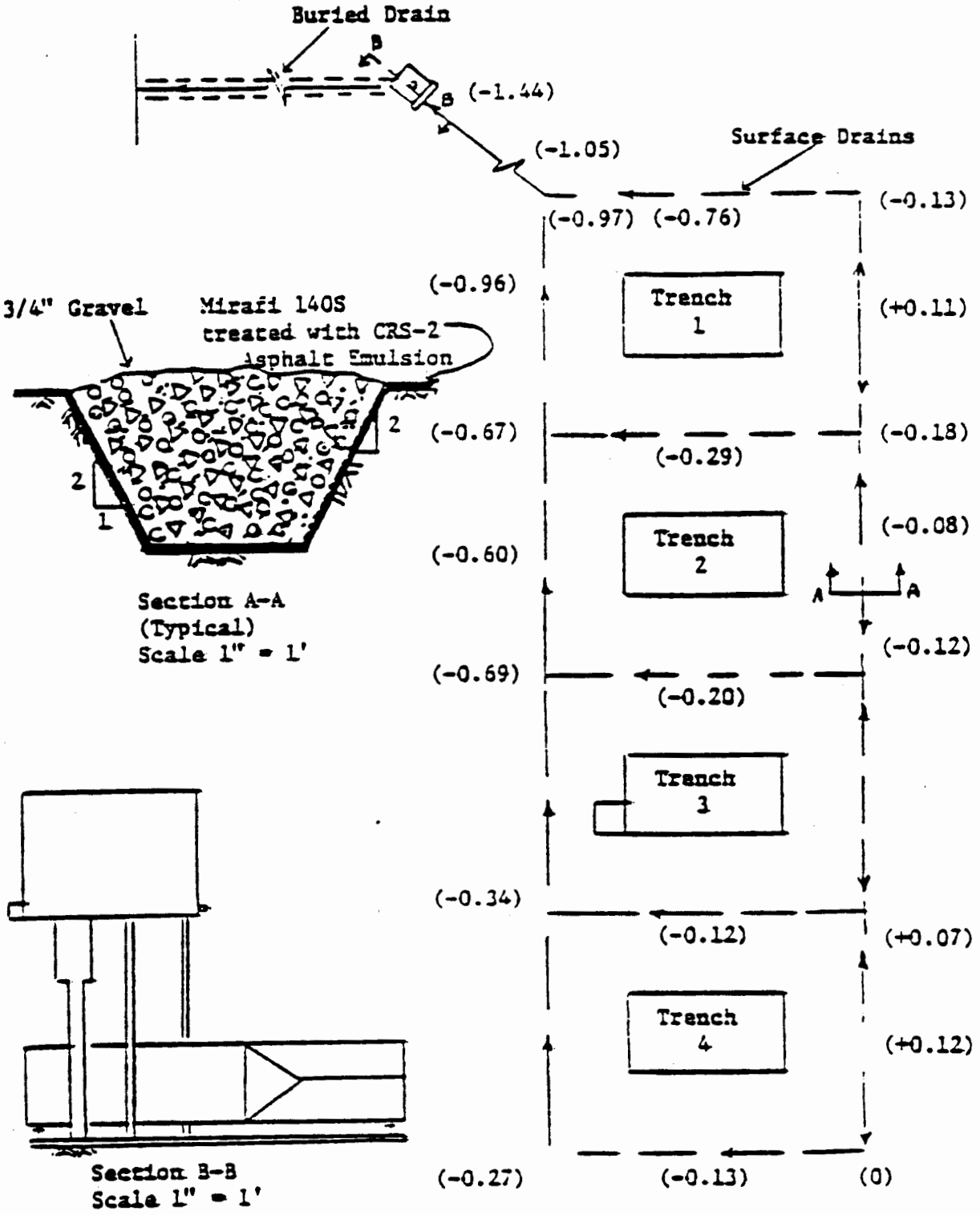
TABLE 2. Summary of Laboratory Test Data.

Soil Property	CGHF Site	ML Site
Unified Soil Classification Designation	SM	SM
Specific Gravity of Solids	2.55	2.55
Uniformity Coefficient	125	5
Shrinkage Limit (%)	20	-
Liquid Limit (%)	20	27
Plastic Limit (%)	23	27
Plasticity Index	3	Nonplastic
Standard Proctor Maximum Dry Density (pcf)	102	101
Standard Proctor Optimum Moisture Content (%)	14.0	15.8
Modified Proctor Maximum Dry Density (pcf)	113	108
Modified Proctor Optimum Moisture Content (%)	13.5	13.4
Unconfined Compressive Strength (psf)	354	1683
Peak Effective Friction Angle (degrees)	33	35
Peak Effective Cohesion Intercept (psf)	1200	240

ML Site

The four trenches at the ML Site are located as shown in Figs. 6 and 7. Due to the heavy forest vegetation and steep, irregular terrain, it was impossible to site the trenches in the orderly way that was done at the CGHF Site. Also, slight modifications in the trench depths and monitoring systems had to be made because of shallow underlying rock masses. Figures 8, 9, 10 and 11 show sections of the "as-built" trench configurations at the ML Site. The numbers in parentheses indicate average elevations of lifts at time of completion of an individual lift and, with respect to settlement plates, the elevations of the bottom of the plate and top of the extension rod at the time of installation. It should be noted that gabled trench crowns were not needed to direct runoff away from the trench areas due to the natural slope of the site. Instead, finished elevations were close to natural grade elevations and soil and rock berms were constructed upslope from the trenches themselves to prevent the formation of erosion rills on the caps from uphill runoff. It is felt that these changes do not affect the objectives of the experiment. Soil backfills were compacted to the same specifications as used for the CGHF Site backfills. Table 2 contains a summary of laboratory test data for the ML Site soils.

Another important design change implemented at the ML Site involves the placement of structural and hydrologic monitoring devices. This will be discussed in more detail in the following section.



Figures in parentheses represent difference in elevation (ft) at bottom of drainage ditch between point indicated and southwest corner of system. Arrows indicate direction of flow. Scale: 1" = 20'

Fig. 5 - Trench Location Plan and Surface Runoff Collection/Drainage System at CGHF Site

perimeter of the trench to prevent the entire beam from sliding off the supports and dropping into the void below it. Otherwise, some form of artificial anchorage, such as pins or staples, must be used.

TRENCH DESIGNS

Four different trench cap configurations were conceived to test the effectiveness of the soil arch and soil beam concepts with respect to structural integrity and water tightness. The trenches were designed to a standard size of approximately 10 feet deep and 20 feet by 10 feet in plan. The differences among the various designs are shown in Figures 2, 3 and 4 and are summarized in Table 1. Trench No. 1 was considered the "baseline" design. In order to evaluate the effects of climatic environment on the efficacy of the various designs, two sets of four different trenches were actually constructed. One set of trenches is located just west of the City of Tucson at the University of Arizona's Casa Grande Highway Farm (CGHF Site); the other set is located at elevation 7800 ft ± in the Santa Catalina Mountains just north of the City of Tucson near Mount Lemmon (ML Site). The former site is located in a desert region having a semi-arid environment (11 inches of rain/year), while the latter site is in a mountainous region having a temperate environment (25 inches of rain/year).

TABLE 1. Summary of Trench Design Features.

Trench Component	Trench Number			
	1	2	3	4
Waste Simulant	Straw	Straw	Collapsible Platform	Straw
Cap	Compacted Soil	Compacted Soil	Compacted Soil	Compacted Soil
Crown	Compacted Soil	Single Strip of Geotextile Overlain by Compacted Soil	Soil Beam Overlain by Compacted Soil	Soil Beam Overlain by Compacted Soil

SITE CHARACTERISTICS AND AS-BUILT TRENCH CONFIGURATIONS

CGHF Site

The four trenches at the CGHF Site were constructed essentially according to the designs shown in Figs. 2, 3, and 4. They are located as shown on the layout in Fig. 5. The thickness of waste simulant ranged from three to four feet, with cap thicknesses of from four to five feet, depending upon the crown design configuration. Crown thicknesses (including the soil beam) varied from approximately 1½ to 2½ feet. In general, the crowns extended five feet in each direction beyond the trench boundaries. The surface of each crown was gabled at a slope of approximately five percent in order to direct runoff away from

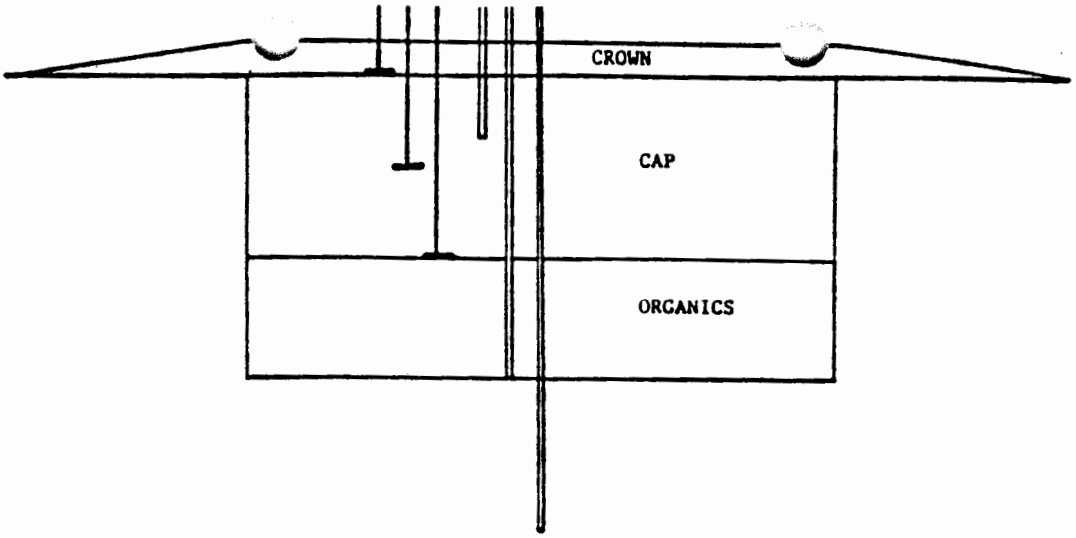


Fig. 2 - Trench No. 1 - Conceptual Design and As-Built Configuration at CGHF Site

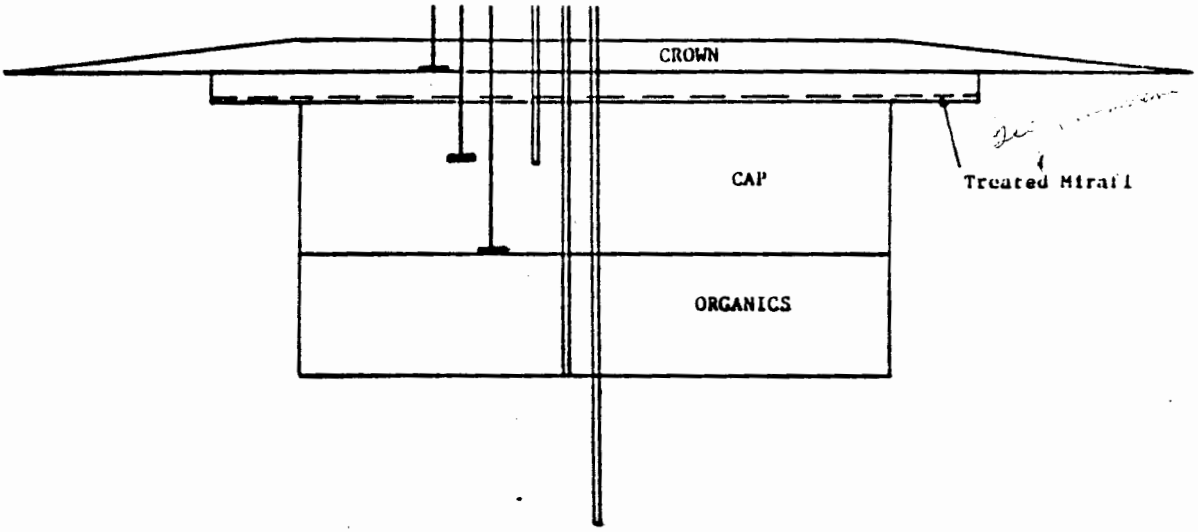


Fig. 3 - Trench No. 2 - Conceptual Design and As-Built Configuration at CGHF Site

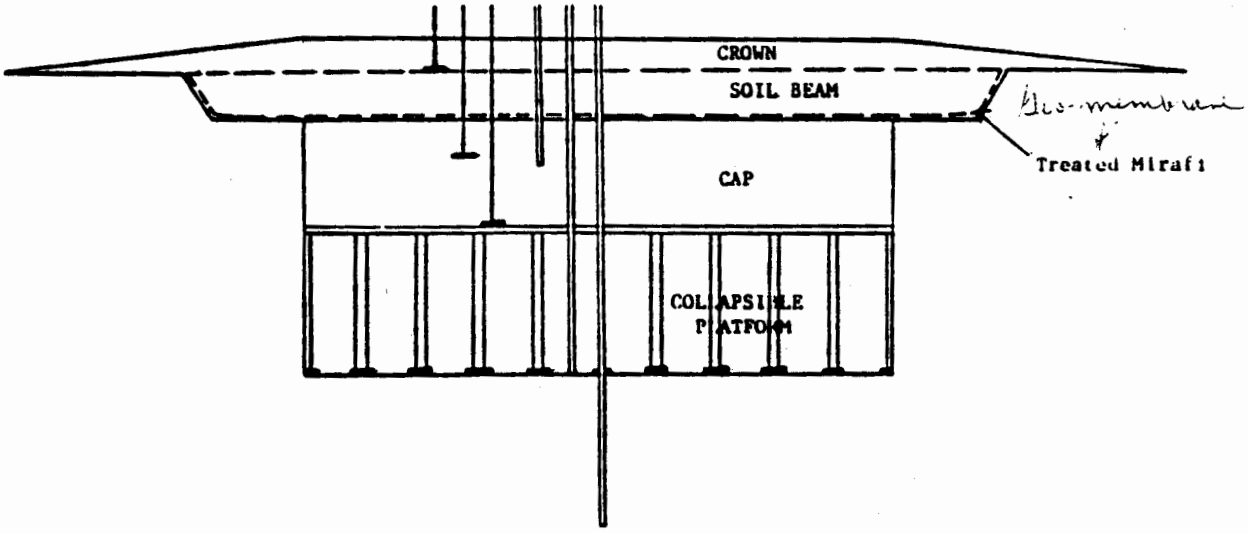


Fig. 4 - Trench No. 3 - Conceptual Design and As-Built Configuration at CGHF Site (Trench No. 4 design is the same except for organics in lieu of collapsible platform.)

weight of the soil prism above the buried structure. It is important to realize, however, that downward movement of the prism relative to the trench sidewalls is required to mobilize the shearing resistance. These concepts form the basis of the "imperfect ditch method" of construction recommended by Marston (1930) and later by Spangler (1958) for the installation of buried pipes or culverts.

When these concepts are applied to shallow-burial, low-level nuclear waste disposal trenches, the following considerations apply:

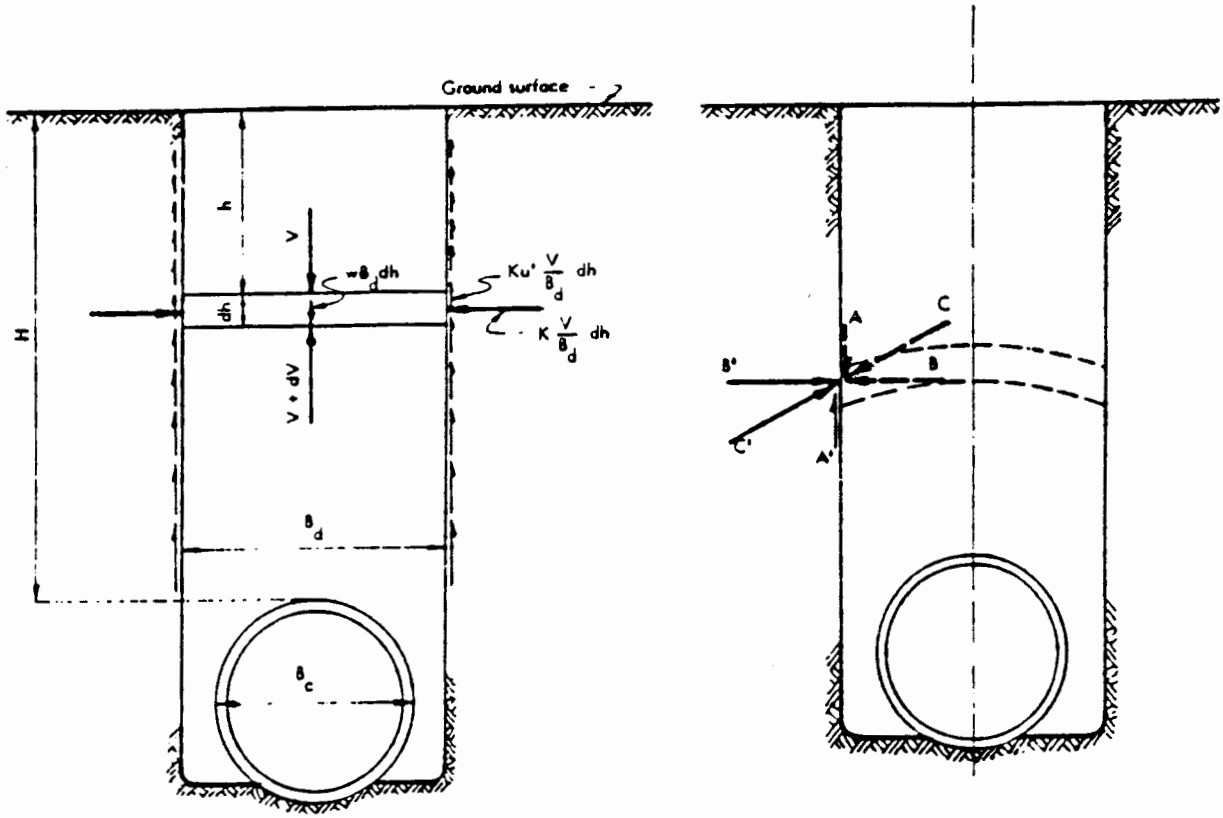
1. Some downward movement of the backfill soil prism or cap is required to mobilize shearing resistance along the cap-trench sidewall interface. If the backfill soil that constitutes the cap is sufficiently compacted, this movement will be due primarily to deflection of the "buried structure"; i.e., consolidation and/or decay of the buried wastes.

2. The better the compaction of the backfill, especially adjacent to the trench sidewalls, the larger will be the interface friction angle (ϕ_d), and the closer it will approach the internal friction angle of the trench sidewall or backfill soils. As indicated by Eq. 1, the larger the value of ϕ_d, the larger the unit shearing resistance along the interface.

3. For a given trench width, B_d, the larger the shearing resistance along the trench sidewall-cap interface, the lower the H/B_d ratio required for arching to occur.

SOIL BEAM CONCEPT

The soil beam concept is predicated on the fact that most soils possess little, if any, tensile strength. Whatever tensile strength soils exhibit is usually due to cohesion which, in most cases, is a transient phenomenon that is highly dependent upon moisture content. Indeed, the tensile strength of soil is never incorporated into civil engineering design, even though laboratory tests on specific soils may indicate it exists. In this respect, the engineering design of soil structures often involves the use of "reinforced earth", a concept similar to that used in the design of concrete structures where steel reinforcement rods resist tensile stresses. In this research, the concept of the soil beam was used in an attempt to provide a basis for the design of a reinforced soil structure that could bridge the void created by decaying buried wastes. Very simply, the soil beam or soil slab is a structural element composed of a layer of compacted soil completely enclosed on four sides by a sheet of geotextile. In this research a woven geotextile, Mirafi 500N , was used. A schematic representation of the soil beam is shown in Fig. 4. In concept, as the material below the soil beam settles, the beam is loaded by its selfweight and the weight of the crown above it. These loads induce tensile stresses below the neutral axis of the beam and compressive stresses above the neutral axis. The compressive strength of the soil itself is able to resist the induced compressive stresses. The geotextile, on the other hand, resists the induced tensile stresses just as the reinforcing rods do in a reinforced concrete beam. The effectiveness of the soil beam, therefore, is limited by the tensile strength of the geotextile and the free span of the beam. Another factor that must be considered is the end support condition; i.e., there must be sufficient overhang of the soil beam around the



$$V = wB_d^2 \frac{1-e^{-2Ku'(h/B_d)}}{2Ku'}$$

e = base of natural logarithms
K = ratio of lateral pressure to vertical pressure
u' = coefficient of friction between backfill and sides of ditch

A Free Body Diagram Ditch Conduit

B Arch Action in Backfill Over a Ditch Conduit

Fig. 1 - Soil Arch Concept (from Spangler, 1963)

SOIL ARCH CONCEPT

When the loads on an underground structure are considered, it would appear that the load due to the soil overburden should be equal to the weight of the soil prism directly above the structure. Experience has shown that, depending upon the flexibility of the structure, the actual resultant load may be greater than or less than the weight of the soil prism. In the latter case, the reduction in load is attributed to an arching phenomenon that occurs in the soil overburden.

The concept of the soil arch derives from the work of Marston and Anderson (1913), Marston (1930) and Spangler (1950, 1958, 1963). The concept was first developed in an attempt to explain why observed values of pressures on buried structures due to soil overburden were often significantly less than those expected from a consideration of the weight of the overlying soil prism alone. It was postulated that the algebraic difference between the weight of backfill and the observed load on the buried structure is due to arching of the soil above the buried structure. Because of this arching, the weight of the soil is directed around and away from the roof of the structure. The lateral and vertical forces which constitute the arch action and arch support at any point below the ground surface are shown in Figures 1a and 1b. The force B shown in Fig. 1b is due to the lateral pressure of the backfill acting over a unit area against the side of the trench and the force B' is its equal and opposite reaction. The force A is the shear force at the point and is equal to B times the tangent of the trench-backfill interface friction angle ($\bar{\phi}_d$). A' is its equal and opposite reaction. The forces C and C' are vector sums of A and B, and A' and B', respectively. The maximum value of the vertical shearing resistance at any point along the trench-backfill interface is determined by the shear strength of the soil at that point as given by the expression

$$\tau = \bar{c} + \bar{\sigma} \tan \bar{\phi}_d \qquad (1)$$

where $\bar{c}$ = unit cohesion

$\bar{\sigma}$ = effective normal stress acting on the interface (horizontal stress for vertical-wall trenches)

$\bar{\phi}_d$ = effective interface friction angle $\leq$ internal friction angle of trench wall soil or backfill soil, whichever is lower.

This maximum value defines the limiting amount of arch support that is available to help carry the weight of the backfill prism. All of the prism weight in excess of the arch support is transmitted to the buried structure at the bottom of the trench. In order to mobilize the shearing resistance along the interface fully, a certain amount of downward movement of the backfill relative to the side walls of the trench is required. This movement is usually due to a combination of factors such as settlement of the structure into its bedding, consolidation of the backfill itself, and/or deflection of the roof of the buried structure. Obviously, the greater the H/B_d ratio (refer to Fig. 1a), the greater the chance that the mobilized shearing resistance (not necessarily the maximum available shearing resistance) along the interface will equal or exceed the

of surface water. Leaching of this surface water through the waste may lead to contamination of both surface water and groundwater supplies. It is clear that in order to reduce the probability of serious radio-nuclide pollution of the biosphere by this method, trenches at shallow-land burial, low-level nuclear waste disposal sites must possess structurally competent caps that have relatively low permeability and high resistance to erosion/weathering.

During the past ten months the University of Arizona, under NRC contract, has constructed eight shallow-land burial trenches of four different types (one set). One set of trenches is located in the vicinity of Tucson at the University of Arizona's Casa Grande Highway Farm (CGHF Site); another set is located in the Santa Catalina Mountains near Mount Lemmon (ML Site). The former site is semi-arid (11 inches of rain/year) while the latter site is temperate (25 inches of rain/year). The concept is to evaluate trench performance at the same time under two different environments.

OBJECTIVES

The principal objectives of the University of Arizona research effort were to develop and evaluate trench designs that would:

1. Minimize surface subsidence and/or cracking. Such subsidence/cracking creates a local "sink" where surface water can collect and subsequently infiltrate the trench. Surface subsidence/cracking is usually a manifestation of one or more of the following factors: consolidation of buried wastes due to overpressures exerted by the backfill with concomitant vertical movement of the backfill; deterioration of buried wastes and/or their containers with resultant formation of subsurface voids and eventual slippage of the trench cap into the void; and, finally, consolidation of the backfill soil under its own weight.

2. Minimize infiltration of surface water. Natural infiltration occurs by water flowing in tortuous paths through interconnected soil voids. Infiltration rates, therefore, may be diminished by one or more of the following methods: reducing the size and spacing of soil voids by controlled compaction of backfill; placing artificial barriers in the path of flow; and directing surface water away from the trench and removing it from the site.

SCOPE OF WORK

In order to accomplish these objectives, three different trench designs and backfilling procedures were investigated in which the concept of the soil arch and/or the soil beam were utilized. Waste decay and therefore trench loading were simulated in two ways: first, by placement of organics (straw) so that long-term effects could be observed; and second, by artificially speeding up the decay process and creating a void by collapsing a wooden platform built to support the cap. All trenches were instrumented with settlement plates so that movements at various locations in the backfill could be monitored. In addition, a program to monitor and measure water movement through the experimental trenches and to develop the procedures needed to implement a prototype monitoring program at an actual waste burial site was developed.

AN APPLICATION OF SOIL ARCH AND SOIL BEAM CONCEPTS TO THE CONSTRUCTION OF SHALLOW LAND BURIAL TRENCH COVERS

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ABSTRACT

Experience with shallow land burial sites indicates that undesirable surface subsidence and cracking of trench caps often occur a relatively short time after completion of backfilling. In the past, backfilling procedures have been rather arbitrary with the result that caps were often not strong enough to sustain themselves following creation of a void beneath them as the wastes decayed. In most cases, these cap failures may have been prevented by some form of soil stabilization at the time of construction.

This paper reports on an investigation in which three different trench cap designs were developed and prototype trenches constructed in two different climatic environments to test the adequacy of the designs. The basic concept underlying each of the designs is that trench cap performance could be improved if the cap were stabilized in some way. In one design, controlled compaction alone was used to achieve high levels of in situ density. In another design, the emplacement of a strip of reinforcing geotextile in addition to controlled compaction was used. The third design incorporated a "soil beam" into the cap in addition to controlled compaction. A soil beam is a structural member constructed of compacted soil surrounded by an overlapping sheet of geotextile. Underlying each of these designs is the concept of a "soil arch". Under proper conditions, soil has the ability to arch itself over small voids within the soil mass with little or no deformation at the surface. In order to test this concept and to evaluate the relative merits of the three designs, a system of settlement plates was installed at various levels in the caps. These settlement plates were monitored during and after construction so that absolute and relative displacements could be determined within a given trench. Differences in behavior among the three trenches could also be observed in this way.

This paper describes the details of the designs and construction procedures. The limited amount of settlement plate data gathered to date is also presented.

INTRODUCTION

It is universally recognized that one of the most common methods of release of radio-nuclides to the biosphere from shallow land burial trenches is through groundwater movement. In areas where the natural groundwater table is well below trench bottom elevation, movement of water into the trench occurs from the surface. The most apparent scenario for such movement is a trench cap failure as buried wastes decay and/or compact, followed by infiltration

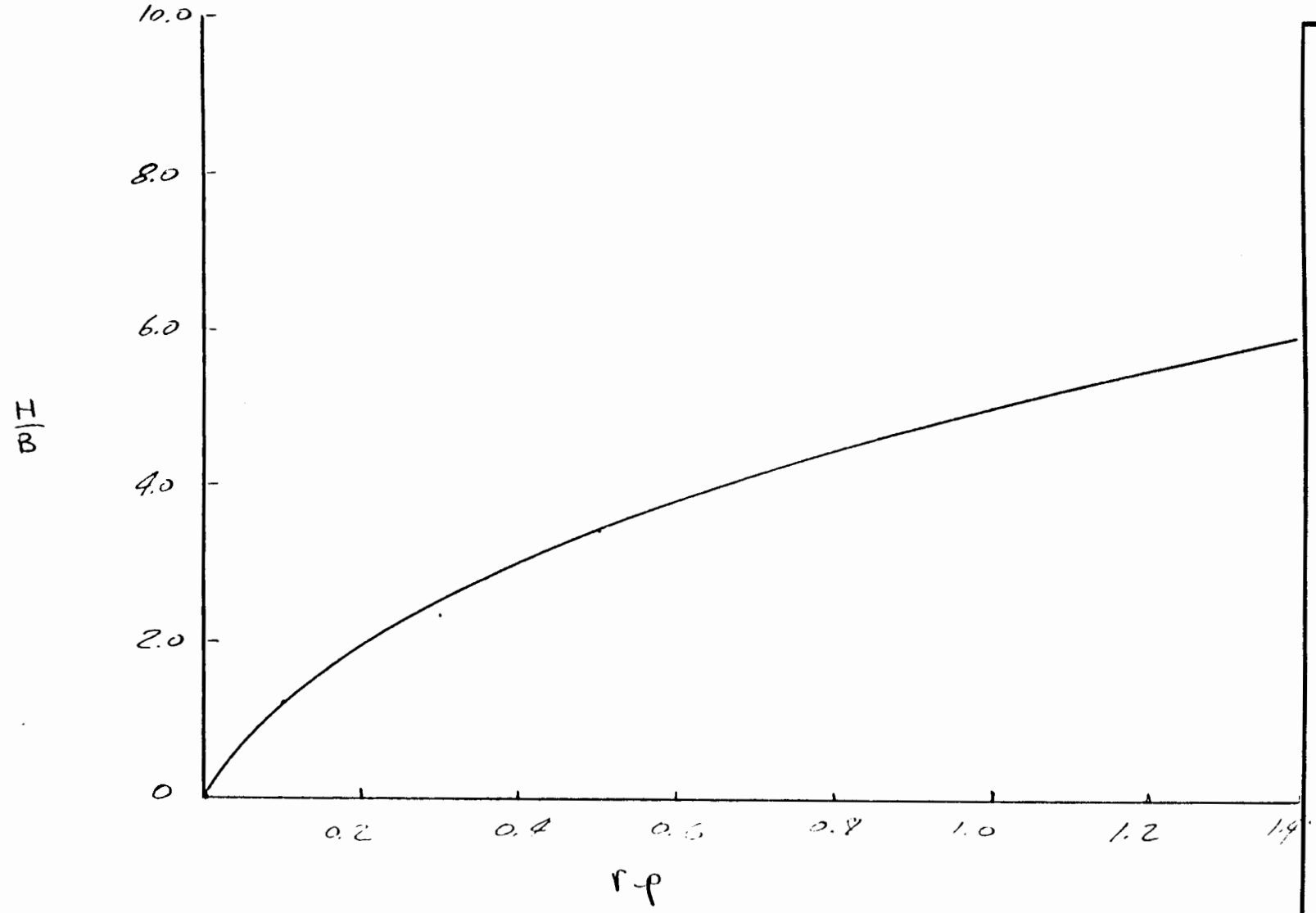

FIG. 3 - HEIGHT OF COVER, H, REQUIRED TO AVOID SURFACE EXPRESSION OF VOID CREATED BY CONTAINER DETERIORATION

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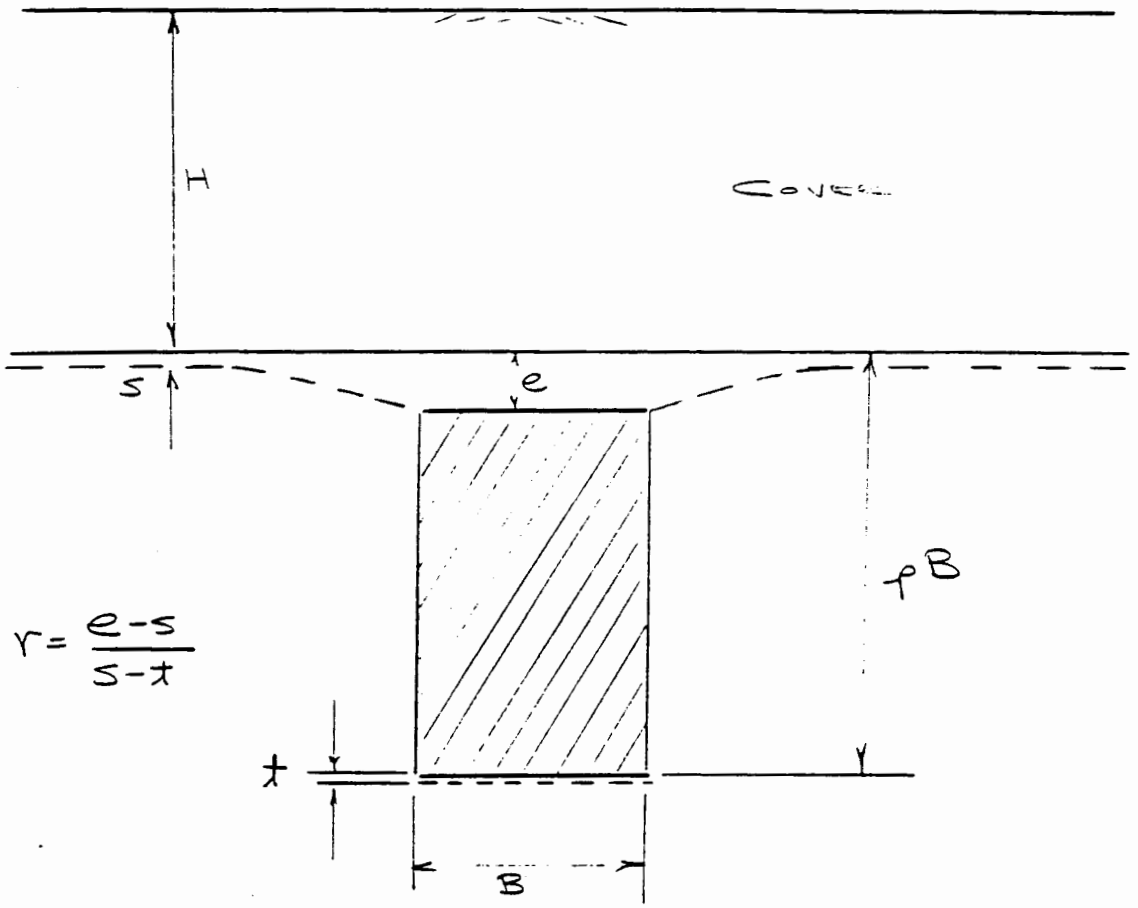

e = VOID CAUSED BY DETERIORATION

s = SETTLEMENT OF BACKFILL

t = SETTLEMENT OF CONTAINER

FIG 2 - DEFINITION OF TERMS FOR APPLICATION OF FIG. 3.

Nutrition & Subsidiary

Slip Cover

Manuscript

Lord Bacon

Miscellaneous

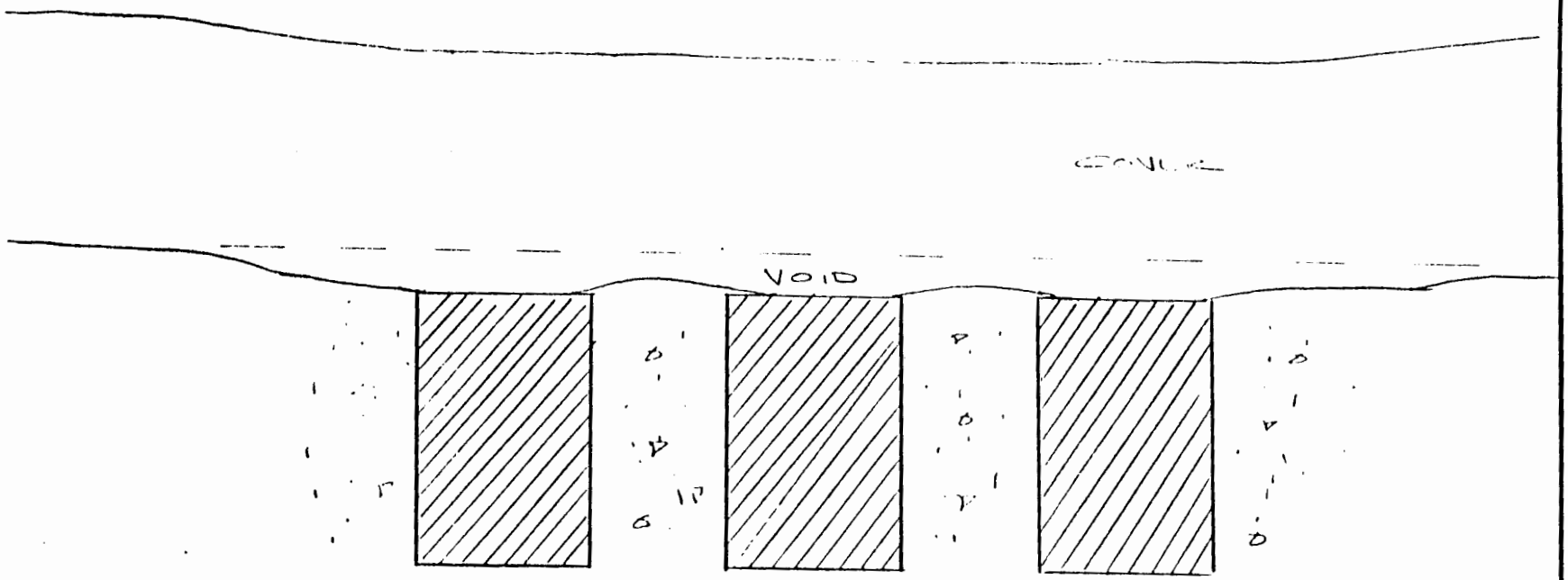

FIG 16 SETTLEMENT OVER LARGE AREA AROUND SEVERAL CONTAINERS WITH COMPRESSIBLE BACKFILL,

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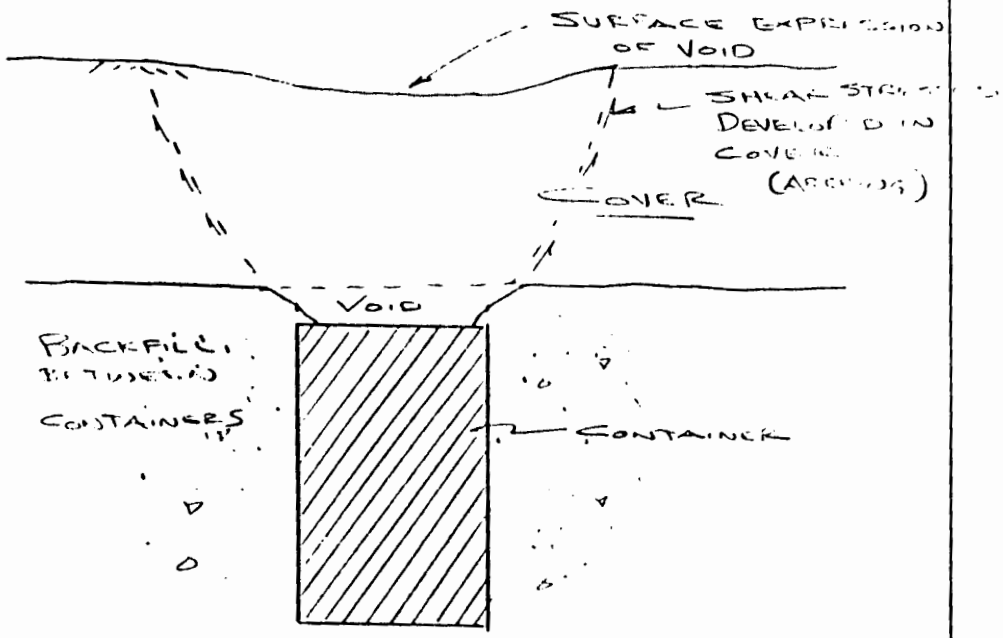

FIG 1a) LOCALIZED SETTLEMENT DUE TO DETERIORATION OF CONTAINER

FIG. 1b on p.

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of height H. After deterioration of this container the top of the container will settle by an amount, e. Marston's theory (Spangler and Handy, 1982) can be used to estimate the approximate height of cover required to provide adequate arching such that the subsidence will not extend to the top. Fig. 3 presents the height, H, relative to the width of the container, B, that is necessary to provide adequate arching. The ratio H/B is a function of the two prameters, r, and p, shown on Fig. 2.

If one were to consider a 55 gallon drum container with a nominal diameter of 24 inches overlain by a cover of 10 feet the value of H/B would be 10/2.0 = 5.0. Thus, in order to avoid surface expression of the container deterioration, values of "rp" corresponding to H/B = 5 would need to be less than 1.0. Factors governing r include the reduction in volume that occurs as the drum deteriorates (i.e. the value of e) and the stiffness of the side backfill around the drum. If several drums are located together such that the effective value of B is large it would be expected that subsidence would reach the surface. However, the subsidence would result over a large area and cracking would not be great. On the other hand, if B is not large, and values of e are sufficiently low, it would be expected that arching will occur in the cover and subsidence at the surface would not occur.

The use of Marston's theory for this particular application would require some research before much confidence could be placed on it. This is especially true for applications to long term problems. However, the use of Fig. 3, with appropriate factors of safety, provides some guidelines as to the general orders of magnitude of settlement that may be expected. These results can be used to support judgemental decisions regarding arching in covers and the potential for subsidence to occur.

<u>Reference</u>:

Spangler, Merlin G. and Handy, Richard L. (1982), <u>Soil Engineering</u>, Chapter 26, Harper & Row, Publishers, New York.

SUBSIDENCE OF EARTH COVER

Deterioration of containers in low level waste facilities will result in a void at the interface between the waste and the cover. The nature of this void and its size will be highly dependent upon the container itself, the nature of the waste in the container, and the method of placement of the container in the waste facility, i.e. whether or not sand is placed around and/or over the container. Fig. 1 demonstrates this.

The differential movement that occurs at the bottom of the cover due to the deterioration may or may not be transmitted to the top of the cover depending upon the nature of the void space created by the container deterioration. Also the magnitude of differential movement at the cover surface and the extent to which it can cause cracking of the cover will depend upon the differential movement between the top of the container and the backfill between containers, the nature of the material above the container, and the actual amount of settlement of the top of the container. If the void space is of large lateral extent as shown in Fig. 1B the cover will act as a beam and will settle by essentially the same amount as the void space that was created. If however, the void space is of limited lateral extent, arching may occur in the cover materials such that subsidence does not reach the ground surface.

On a large scale this problem has been solved for applications in mining. The phenomenon of arching to a stable configuration such that surface subsidence does not occur has been observed, However, on a small scale such as would be encountered at a low level waste facility, the phenomenon is similar and can be analyzed, at least preliminarily, by methods that have been developed fordeformation of culverts under embankments.

This method of analysis has been presented in Spangler and Handy (1982). It has been modified slightly as presented herein for application to covers of low level waste facilities. Fig. 2 shows a container overlain by a cover

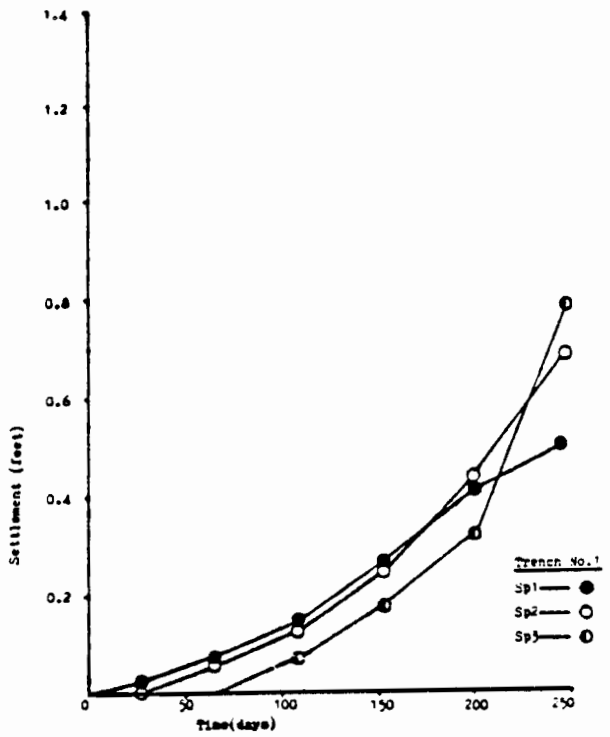

Fig. 12 - Settlement vs Time After Installation of SP1 CGHF Site - Trench No. 1

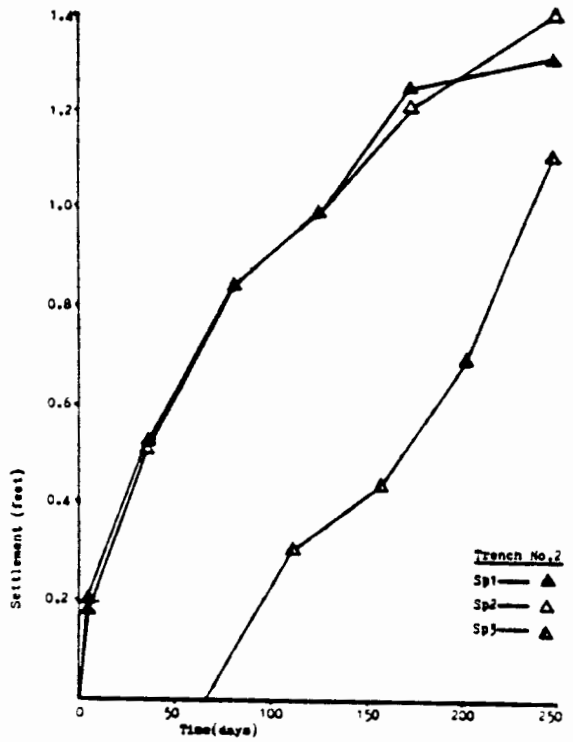

Fig. 13 - Settlement vs Time After Installation of SP1 CGHF Site - Trench No. 2

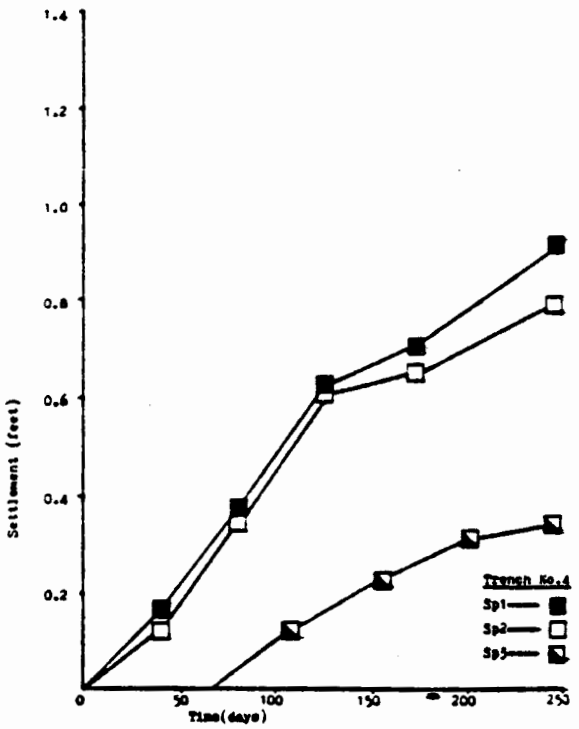

Fig. 14 - Settlement vs Time After Installation of SP1 CGHF Site - Trench No. 4

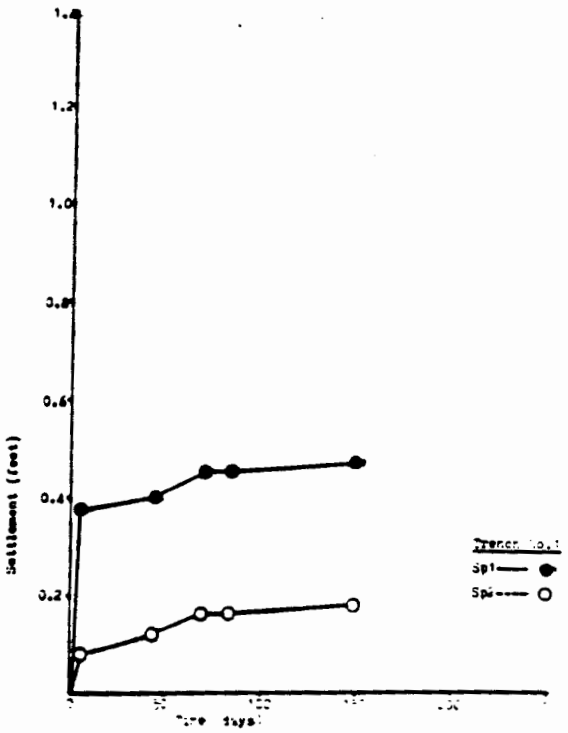

Fig. 15 - Settlement vs Time After Installation of SP1 ML Site - Trench No. 1

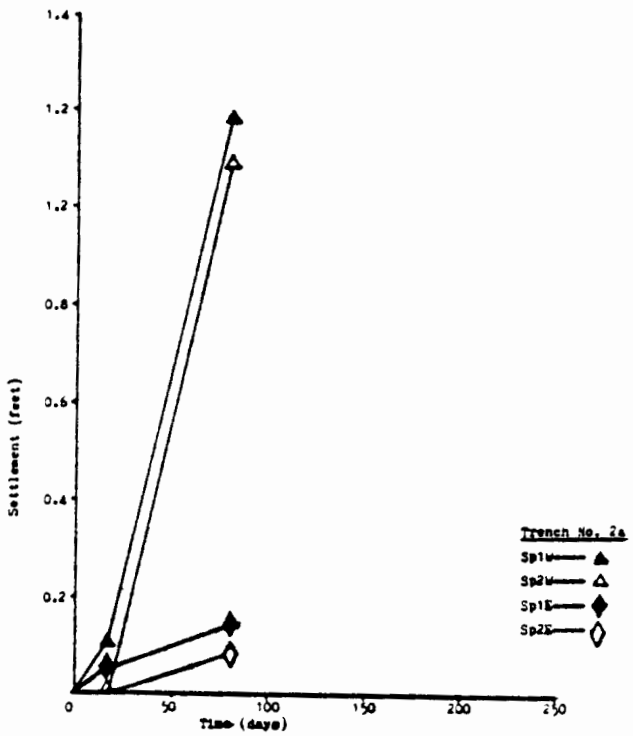

Fig. 16 - Settlement vs Time After Installation of SP1 ML Site - Trench No. 2a

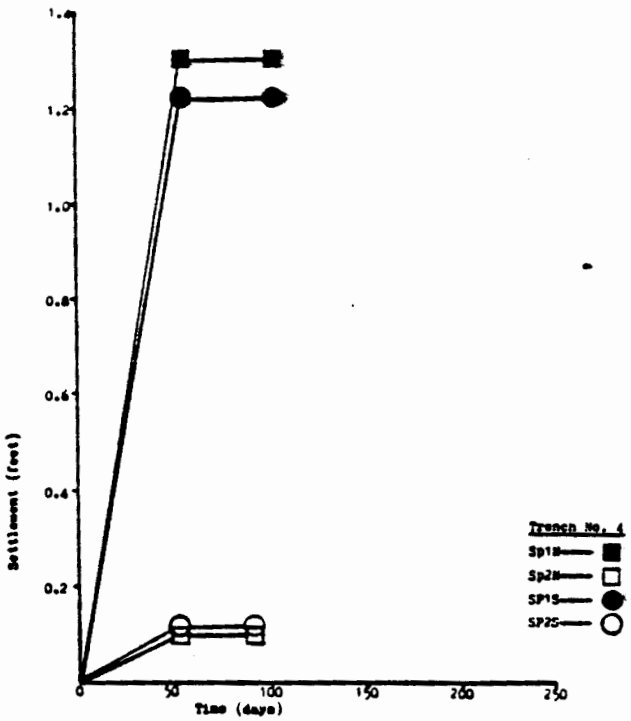

Fig. 17 - Settlement vs Time After Installation of SP1 ML Site - Trench No. 4

settlement plate data collected for those trenches up until the beginning of September. The same general conclusion may be drawn from these limited data as was indicated by the CGHF results, namely, that Trench No. 4 is outperforming all of the other trenches. In addition, a comparison of the slopes of the settlement vs time curves for SP1 and SP2 suggests that soil arches may be forming in all of the trenches at the ML Site since the former slope is steeper than the latter in every case. Again, data are not presented for Trench No. 3 for the same reasons given previously for its counterpart at the CGHF Site.

Comparative Analysis

All of the trenches at the ML Site appear to be functioning better than their respective counterparts at the CGHF Site over similar time intervals. For example, 84 days after the date of installation of SP1 and SP2 in Trench No. 1 at the ML Site, the settlement of SP2 as a percentage of SP1 was approximately 35%. The percentage for Trench No. 1 at the CGHF Site over the same time period was approximately 82%. The better performance is occurring in spite of the fact that the environmental conditions at the ML Site are more severe than those at the CGHF Site, especially with regard to the amount of rainfall. The better performance is attributed to the fact that during construction at the ML Site, the moisture content of the backfill soil was uniform and very nearly the same as that of the soil composing the trench sidewalls. In addition, the in situ density of the trench walls was approximately the same as the compacted density of the backfill. Therefore, a good bond between the backfill and the trench wall could be obtained so that the interface friction angle was probably very close to the internal friction angle of the backfill and/or trench wall soils. If so, conditions are ideal for the formation of a soil arch, which, as indicated previously, seems to be occurring at the ML Site.

On the other hand, large amounts of water had to be added to the backfill soils at the CGHF Site in order to bring the moisture content up to that specified for proper compaction. Because of the relatively small scale construction effort, the added water could not be distributed uniformly during preparation of the backfill material. Moreover, the in situ moisture content of the trench sidewall soils was significantly lower than that of the backfill materials. Therefore, shear strength parameters along the interface between the two were probably different from those determined in the lab for the compacted backfill. Additionally, because of the nonuniformity of moisture content in the backfill, it is possible that shear strength parameters on the interface varied significantly from place to place. Under these conditions, it is very unlikely that significant soil arching could occur.

CONCLUSIONS

Preliminary results indicate that the "soil arch" and "soil beam" are viable concepts that can be utilized in the design of shallow-burial, low-level nuclear waste disposal trenches to decrease the amount of surface subsidence due to decaying and/or consolidating buried wastes. The experiments also suggest that a moisture content mismatch between trench sidewall and backfill soils may be deleterious to the formation of a soil arch. Additionally, the tests indicate that neither concept is valid under extreme loading conditions, such as those imposed by the virtually instantaneous formation of a subsurface void.

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PANEL DISCUSSION

PANEL DISCUSSION

V. C. Rogers: What assurance do we have that the engineered layered cover techniques will reduce infiltration? Do we have any data or assurance that those engineered-typed cover barriers will maintain their integrity and their effectiveness for many centuries?

T. M. Johnson: A field project is currently underway to test the effectiveness of layered covers in limiting infiltration. Certainly, the permeability of the uppermost layer or layers will slowly increase in response to weathering and vegetative growth. The underlying layer, if it remains intact, will probably constitute the long-term cover for the site. Hopefully, the gravel layer will also continue to divert water.

V. C. Rogers: Are there geological analogs or similar things to lend supporting evidence that engineered covers could be effective for quite some time?

T. M. Johnson: There are many of them, but unfortunately they don't have collapsible barrels underneath them.

M. A. Feraday: Why did you use a flat beam rather than a curved beam concept for your soil beams?

E. Nowatzki: If you consider the soil beam to be analogous to a reinforced concrete beam, the geotextile at the bottom of the beam is like the steel reinforcing bars; that is, it would go into tension as the beam tended to bend under its self-weight. If we had curved the geotextile concave down, it wouldn't have been doing that. It would have been compressing instead as the displacements were taking place.

M. A. Feraday: But what if they were curved up as on a normal cap?

E. Nowatzki: The condition is the same as that I just described. The beam would have to go through a complete curvature change before the geotextile at the bottom could carry a load, because the geotextile has no compressive strength.

M. A. Feraday: Would continous rain have much effect over a long period of time on a beam like that?

E. Nowatzki: I don't believe so. There's an increase in weight by the amount of moisture that's absorbed into the soil beam and overlying crown. Where rainfall hurt us on the experiment was on the interface. The moisture destroyed shear resistance on the interface.

D. E. Fields: What other thoughts do some of you have on preventing human intrusion or at least notifying the intruder that he has done something he might wish to reconsider? Has anyone thought, for example, of using very stable dyes distributed in a thin layer over the waste, or using odoriferous material that might repel the intruder?

T. E. Hakonson: I don't have anything concrete to recommend for preventing human intrusion. The suggestion to bury warning devices such as glass discs is the best I can offer.

Intrusion problems that currently exist at low-level waste sites involve plants and animals. Those problems are real, they can be demonstrated, and they require solutions. The human intrusion problem is one I am not qualified to discuss.

E. Nowatzki: We have a human intrusion problem of a sort with our experiments at the Mount Lemmon site, which is in a recreational national forest. There are all kinds of people walking around, and we've been trying to figure out ways of keeping them from walking all over our experiments.

One of the ways suggested, which we obviously couldn't do, was to put up "Radiation" signs to scare people away.

R. S. Skryness: Another method for precluding possible human intrusion takes place during site characterization. Locating sites in areas that do not have any economic resources or materials that may be useful in the future would be one way to prevent the intruder looking for useful materials.

W. F. Lawless: Regarding biointrusion, have you been able to look at modeling prospects, and how difficult are these projects?

T. E. Hakonson: We have not attempted to model biointrusion at low-level waste sites. There are a tremendous number of variables that would make such an attempt difficult.

Both Savannah River and Los Alamos have site models which include biotic transport based upon studies of uptake of radionucles by biota. Some of the problems with such an attempt are that transport of radionuclides to biota varies by chemical species, biota species, space, and time. In addition, if one assumes that biological intrusion barriers work, then it follows that the rate constants describing radionuclide transport to biota are zero.

The effort we do have in modeling relates to water dynamics and the influence of vegetation in controlling the water balance.

I'd like to offer one additional thought about the concept of constructing a low-level waste site cover that minimizes erosion, water infiltration, and biological intrusion. I believe that the key to building a low-level waste site that minimizes water and biota-related problems is the vegetation cover. In a DOE information meeting in Denver in early September, I introduced the concept of the "super plant." What is needed is a plant species, or plant community, that is shallow rooted (i.e., confined to the cover soil that is optimized for moisture storage capacity), has a maximum transpiration potential, prevents invasion of the site by undesirable plant species (allellopathy), and discourages burrowing animals (undesirable habitat for such animals). It seems to me that we need to take advantage of attributes of natural vegetation that show some or all of the above requirements to minimize water and biota-related problems. At least some of the engineered barriers which are routinely discussed for preventing water and biota-related problems have never been tested at field scale and as a function of time.

L. J. Mezga: The name of that species is what?

T. E. Hakonson: An evergreen species such as Ponderosa pine exhibits many of the desirable features of that "super plant." The point I wish to make is that some species are much better qualified as "super plants" than others. We need to identify these species to take advantage of them in designing stable burial sites.