Hydrology of a waste rock repository capping system at the Zortman Mine
by Elizabeth Anne Warnemuende

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Rehabilitation
Montana State University

Abstract:
Waste rock produced by the mining industry may contain sulfide minerals, which often oxidize to produce acid in the presence of water. This acid production may lead to acid rock drainage. Therefore, it is important to dispose of sulfide - rich waste rock in a way that will minimize exposure to water and the consequent release of acid rock drainage into the environment.

The 300 - foot thick Mill Gulch waste rock repository at the Zortman Mine was capped with a series of oxidized and clayey materials in 1992. The cap was designed to minimize infiltration of water into the repository and thus minimize the probability of acid rock drainage. The purpose of this investigation was to evaluate the hydrology of the Mill Gulch waste rock repository in order to determine whether the capping system adequately precludes infiltration of precipitation into the repository so as to prevent gravitational drainage of water from the repository.

Repository water content was measured monthly over a 12 month monitoring period using a neutron probe. Neutron probe data were collected from eight neutron probe access tubes located on three different terraces on the Mill Gulch waste rock repbsitoiy. Neutron tubes varied in depth from 70 to 310 feet.

A laboratory method for neutron probe calibration in unconsolidated waste rock was developed. A fifty gallon sample of waste rock was oven dried and loaded into a monitoring barrel, which was equipped with time domain reflectometry probes and a neutron probe access tube for the entire profile. The response of time domain reflectometry and neutron probe measurements to calculated volumetric water additions was monitored following additions of 0.5 % volumetric water increments.

A neutron probe calibration for the waste rock material was successfully generated. The relationship between the neutron count ratio and volumetric water content was found to be linear with $r = 0.96$. The results of the hydrologic study indicated that much of the Mill Gulch waste rock was at or above field capacity; thus water will drain downward in response to gravity. Average drainage from the repository was estimated to be less than the 14.3 inches of precipitation received during the monitoring period. The capping system is thought to be effective at storing infiltration and promoting runoff from the repository. In addition to precipitation, the repository received run - on from a large unreclaimed topsoil stockpile located up gradient from the top bench of the repository. Run - on contributed to infiltration at the repository top.

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Master of Science

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Land Rehabilitation

MONTANA STATE UNIVERSITY-BOZEMAN
Bozeman, Montana

December 1997

APPROVAL

of a thesis submitted by

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date 12-4-97

ACKNOWLEDGMENTS

I would like to thank my mother for answering hundreds of impossible childhood questions with "go to school and find out," and my father for the countless kitchen table tutoring sessions which made that a reasonable request.

Additionally, I am thankful to Dr. Douglas Dollhopf for providing me with the opportunities and skills I needed to take on this project, my committee members and the Reclamation Research Unit at Montana State University for their expertise and patience, and Clark Armstrong and John Goering for their assistance in consistently wretched field weather.

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ABSTRACT

Waste rock produced by the mining industry may contain sulfide minerals, which often oxidize to produce acid in the presence of water. This acid production may lead to acid rock drainage. Therefore, it is important to dispose of sulfide - rich waste rock in a way that will minimize exposure to water and the consequent release of acid rock drainage into the environment.

The 300 - foot thick Mill Gulch waste rock repository at the Zortman Mine was capped with a series of oxidized and clayey materials in 1992. The cap was designed to minimize infiltration of water into the repository and thus minimize the probability of acid rock drainage. The purpose of this investigation was to evaluate the hydrology of the Mill Gulch waste rock repository in order to determine whether the capping system adequately precludes infiltration of precipitation into the repository so as to prevent gravitational drainage of water from the repository.

Repository water content was measured monthly over a 12 month monitoring period using a neutron probe. Neutron probe data were collected from eight neutron probe access tubes located on three different terraces on the Mill Gulch waste rock repository. Neutron tubes varied in depth from 70 to 310 feet.

A laboratory method for neutron probe calibration in unconsolidated waste rock was developed. A fifty gallon sample of waste rock was oven dried and loaded into a monitoring barrel, which was equipped with time domain reflectometry probes and a neutron probe access tube for the entire profile. The response of time domain reflectometry and neutron probe measurements to calculated volumetric water additions was monitored following additions of 0.5 % volumetric water increments.

A neutron probe calibration for the waste rock material was successfully generated. The relationship between the neutron count ratio and volumetric water content was found to be linear with $r = 0.96$. The results of the hydrologic study indicated that much of the Mill Gulch waste rock was at or above field capacity; thus water will drain downward in response to gravity. Average drainage from the repository was estimated to be less than the 14.3 inches of precipitation received during the monitoring period. The capping system is thought to be effective at storing infiltration and promoting runoff from the repository. In addition to precipitation, the repository received run – on from a large unreclaimed topsoil stockpile located up gradient from the top bench of the repository. Run – on contributed to infiltration at the repository top.

INTRODUCTION

The Zortman mine is located approximately 150 miles north of Billings, Montana in the Little Rockies mountain range. The Mill Gulch waste rock repository at the Zortman mine contains sulfide - rich minerals which, if left exposed to water and oxygen, could produce acid rock drainage. The repository consists largely of a cyanite porphyry, which has pyrite mineralogy. The repository was capped with 18 to 36 inches of Emerson shale, 24 to 36 inches of oxidized waste rock, and 12 inches of coversoil in order to minimize infiltration of precipitation into the repository and subsequent downward drainage of water from the repository. The repository top and benches have an additional polyvinyl chloride (PVC) geomembrane liner overlying the Emmerson shale layer. Exclusion of precipitation from the repository may slow the rate of acid production, which results from the oxidation and hydrolysis of pyrite by the chemical reaction:

$$FeS_2 + 15/4\ O_2 + 7/2\ H_2O \Rightarrow Fe(OH)_3 + 4H^+ + 2SO_4^{-2}$$

This study was conducted to evaluate the hydrology of the Mill Gulch waste rock repository in order to determine whether drainage of water through the repository is likely to occur.

Objectives

1) Develop a neutron probe calibration to estimate the volumetric water content of Mill Gulch waste rock.

- Using time domain reflectometry, develop a laboratory neutron probe calibration for Mill Gulch waste rock with which to interpret neutron probe data.
- Evaluate laboratory water retention and drainage data in order to assess the desorption characteristics of Mill Gulch waste rock.

2) Determine whether the Mill Gulch waste rock repository capping system minimizes infiltration of precipitation into the repository and subsequent downward drainage of water.

3) Estimate the quantity of drainage from the Mill Gulch waste rock repository over a 12 month monitoring period.

BACKGROUND

Climatic Conditions

The Zortman mine is located in a semiarid region of north-central Montana. The top of the Mill Gulch repository is at an elevation of 5025 feet. During the study period analyzed (May 1996 - May1997), the Mill Gulch repository received 14.72 inches of precipitation. Precipitation during January, February, and March was typically snowfall. The average annual precipitation during 1995 and 1996 was 20.34 inches. The 14.72 inches of precipitation received during the period of analysis was unusually low in comparison to the 30 year average annual precipitation (1941 - 1970) for the area, which has been reported by the United States Soil Conservation Service (1980) to be greater than 20 but less than 22 inches.

Site Description

The Mill Gulch waste rock repository was constructed as a head - of - valley fill and has a maximum thickness of approximately 300 feet at the outer edge of the repository top and thins towards the toe of the fill. The entire repository was capped using a sequence of materials (Figure 1). An 18 to 36 inch clayey barrier which consists of

Emmerson shale immediately overlies the waste rock. A two to three foot thick layer of low sulfur oxidized waste rock was placed on top of the shale, followed by twelve inches of coversoil. The repository was constructed with four terraces, in order to minimize erosion and the development of rills and gullies from runoff (Figure 2). Benches are back sloped into the repository and sloped down gradient in order to facilitate removal of runoff from the repository. A PVC geomembrane was added to the capping regime on the repository top and terraces, where water is otherwise less likely to run off than on slopes. This geomembrane immediately overlies the Emmerson shale.

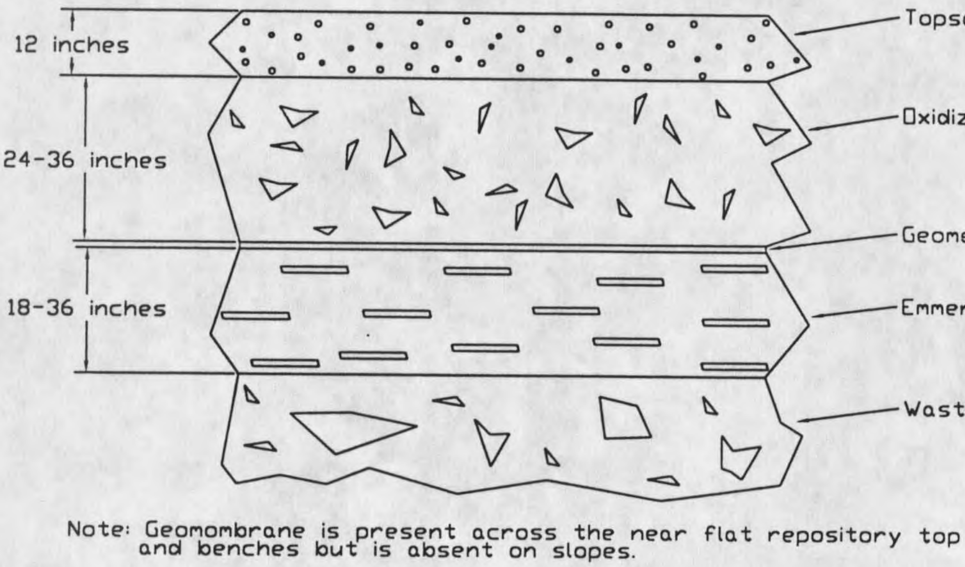

Figure 1. The capping sequence used at the Mill Gulch waste rock repository.

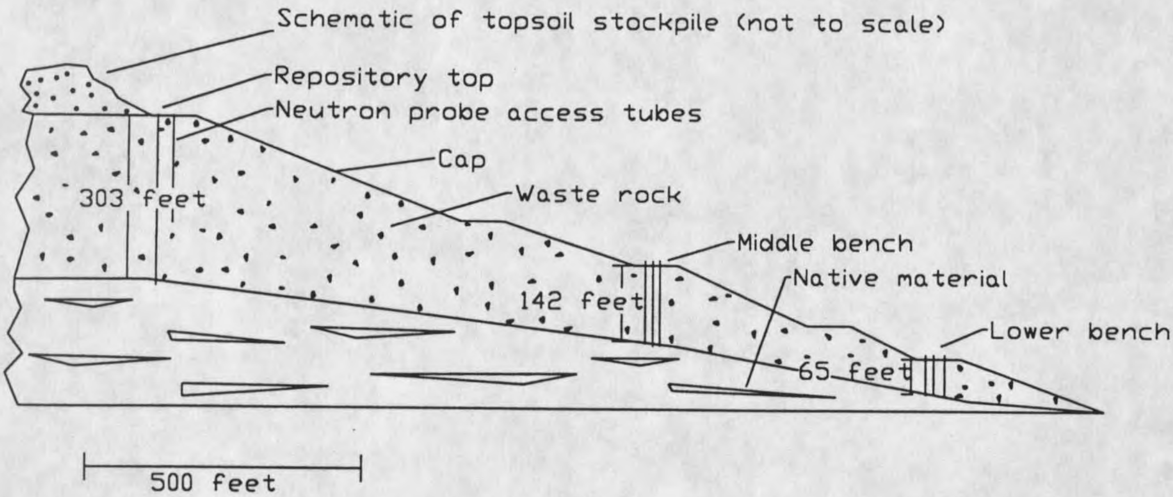

Figure 2. A cross section of the Mill Gulch waste rock repository.

LITERATURE REVIEW

Cap Hydrology

Research has demonstrated that clay caps may not provide a significantly more effective infiltration barrier for tailings impoundments located in areas of low precipitation than capping systems comprised of non - acid producing fill material and coversoil (Dollhopf et al., 1995). These investigators conducted a study at the Golden Sunlight Mine near Whitehall, Montana in order to evaluate the hydrology of several capping systems for a tailings impoundment and to characterize the quantity of recharge into the impoundment under three different capping systems and one uncapped control. The impoundment was designed to minimize infiltration into the tailings and the subsequent oxidation of the tailings materials, which results in acid production.

The capping systems evaluated by Dollhopf, et al. included: 1) a cover consisting of a 55 inch layer of oxidized waste rock followed by a 28 inch layer of coversoil, 2) a cover consisting of a 32 inch layer of waste rock followed by a 28 inch layer of clay and a 30 inch layer of coversoil, and 3) a 50 inch layer of borrow material followed by a 20 inch layer of coversoil. A control plot without any cap was also evaluated. It was found that a cap was necessary to preclude precipitation from the impoundment, but that the clay barrier did not significantly enhance the effectiveness of the cap (Dollhopf et al., 1995).

Capping systems in arid and semiarid regions are often less elaborate then their higher precipitation counterparts. In drier regions, where annual potential evapotranspiration often exceeds precipitation, elaborate capping systems are often deemed unnecessary. However, studies have shown that infiltration through a cap or other porous media is influenced by many factors other than mean annual potential evapotranspiration and precipitation. These factors include: seasonality of precipitation, piston flow, vegetation, and preferential flow (Stephens, 1994).

In areas where mean annual potential evapotranspiration exceeds mean annual precipitation, the season during which precipitation is received plays an important role. If precipitation is most intense during low temperature months, when evapotranspiration is low, potential infiltration will be higher than that of regions with similar water budget, but receiving primarily warm season precipitation. Nichols (1987) found deep percolation occurring on a site receiving less annual precipitation than potential evapotranspiration. The site received proportionally high March precipitation, which exceeded seasonal potential evaporation. Similarly, deep percolation can occur in arid to semiarid regions of proportionally high snowfall because snow melt contributes to high soil moisture during the early spring months when temperature and evapotranspiration are low (Hakonson, et al., 1992).

Soil water often moves through a profile as piston flow. By this process, water added to the soil surface moves downward through the profile by displacing antecedent soil moisture. Soil water content may not change as a function of added water. Stephens

(1985) showed that piston flow may allow infiltrated water to move downward through a soil profile which is less wet than the field capacity water content.

Vegetation plays a crucial role in determining the quantity of infiltration through a soil profile (Stephens, 1994). Studies have shown that deep rooted plants are more effective at preventing deep percolation than shallow rooted grasses. Gee et al. (1989) found that deep percolation through coarse soils with sparse grassy cover accounted for most of the water received by the site, while deep rooted shrubs were more effective at intercepting percolation.

Macropores formed on a cap by plant roots, small animals, or fissures resulting from freeze thaw cycles can facilitate preferential flow, effectively raising the rate of infiltration through the cap. Studies have shown preferential flow can account for 50 to 99 percent of deep percolation through a soil profile (Sharma, et al., 1987).

Neutron Probe

The neutron probe is one of the most accurate tools for measuring volumetric water content through a soil profile commonly used (Carrijo and Cuenca, 1992). The neutron probe can be lowered to any depth in a soil profile through an access tube to obtain volumetric water content data for that depth. The neutron probe consists of a radioactive source, which emits fast neutrons, and a detector tube, which counts slow neutrons. Fast neutrons thermalize to become slow neutrons when they collide with hydrogen nuclei. Because the vast majority of hydrogen atoms in a soil profile are contained in water molecules of the soil water, volumetric water content can be calculated as a function of the ratio of slow neutron count to a background count obtained with the probe in its shield. However, because a soil may contain other sources of hydrogen and non - hydrogen substances capable of thermalizing fast neutrons, a soil specific neutron calibration is required for every soil monitored. Neutron probe calibration is the dominating source of error in volumetric water content measurements obtained by the neutron probe technique (Haverkamp et al., 1984).

A hydrologic study of a waste rock repository was conducted by Schafer and Associates at the Golden Sunlight mine in Whitehall, Montana. Neutron probe access tubes were installed at seven sites on the repository located on both reclaimed and unreclaimed portions of the repository, and monitored for one year. Results indicated reduced infiltration on the regraded, capped, and revegetated portions of the repository as compared to the unreclaimed portions of the repository (Schafer and Associates, 1995). A field neutron probe calibration was developed for this study. The investigators were able to obtain 13 field calibration data points, most of which were between 3.5 and 8.5 percent volumetric water content. Although particle size in the repository was highly heterogeneous, a single neutron probe calibration was used for the entire repository. The field calibration is given in Equation 1, where θ_v equals volumetric water content and NCR equals neutron count ratio. This calibration had a correlation coefficient of 0.77.

$$\theta_v = 19.7 \times NCR + 2.3 \qquad [1]$$

Time Domain Reflectometry

Time domain reflectometry (TDR) is a technique for measuring volumetric water content in soils. The propagation velocity of an electromagnetic pulse along a burried transmission line is measured and used to calculate the dielectric constant of the soil. The dielectric constant is then used to calculate volumetric water content using an empirical calibration equation.

Because the soil bulk dielectric constant is dominated by the dielectric constant of soil water, the dielectric constant of any soil is mainly a function of the volumetric water content. Topp et al. (1980) developed an empirical relationship between the volumetric water content and bulk dielectric constant of the soil. This relationship is given by the third order polynomial relationship in Equation 2, where θ_v equals the volumetric water content of the soil, and ε_b equals the soil bulk dielectric constant.

$$\theta_{vTDR} = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}\,\varepsilon_b - 5.5 \times 10^{-4}\,\varepsilon_b^{\,2} + 4.3 \times 10^{-6}\,\varepsilon_b^{\,3} \qquad [2]$$

Because the dielectric constant of a soil is primarily a function of soil water (Topp and Davis, 1985), which has a dielectric constant about 20 times greater than mineral materials, dielectric constant does not vary greatly with mineral makeup. Topp and Davis (1985) also discovered that the dielectric constant of a soil does not vary significantly with temperature, soil type, or density. Minor changes in soil bulk dielectric constant due to temperature were detected by Pepin et al. (1995). The temperature effect was found to increase with soil water content. Research has shown that dielectric constant does not vary significantly among soil textures ranging from clays to sandy gravels. Drungil et al. (1989) found that the empirical TDR calibration expressed in Equation 1 was applicable to gravelly soils containing coarse fragments.

A physically based TDR calibration was developed by Roth et al., (1990) which accounted for the porosity of the material and the geometric orientation of the probe in relation to the natural layering of the material. According to this model, the volumetric water content of the material is a function of the bulk dielectric constants of all three physical phases within the system, the porosity of the material, and the geometric orientation of the probe. This model produced a calibration curve which is very similar to Topp's calibration for volumetric water contents less than 50 percent (Or and Wraith, 1996).

In time domain reflectometry, electromagnetic pulses are generated by a coaxial cable testing unit (TDR instrument) and transmitted through a coaxial cable to a probe which is inserted in the soil. Both two - rod and three - rod probes have been found to yield accurate time domain reflectometry data. (Kirkschether, 1960), (Zegelin et al., 1989). Reflection waveforms from the electromagnetic pulses are by the instrument and interpreted to estimate pulse propagation velocity. Waveforms are sometimes difficult to interpret. Reflections from the cable to probe interface, soil to air surface and other discontinuities, including large voids that may exist in waste rock, can complicate waveforms to an extent which poses a risk for misinterpretation and false readings.

One method for minimizing risks of misinterpreting TDR waveforms is to create a short circuit at the cable to probe interface in order to determine the point on the waveform that represents the beginning of the probe (Hook et al., 1992). Similarly, short circuiting the end of the probe can be used to identify the point on the waveform representing the end of the probe. A differential technique, such as waveform subtraction enhances the accuracy of waveform interpretation (Hook et al., 1992). In this method, the waveform of the shorted reflection is subtracted from the waveform of the unshorted reflection in order to locate the point on the waveform representing the location of the short circuit. This allows distinguishing of reflections off the cable to probe interface and probe end from extraneous reflections within the measurement zone. A study by Hook et al. (1992) employed shorting techniques coupled with differential techniques to simplify waveforms and identify correct reflections. They found that these techniques "allow easy and reliable waveform interpretation by unskilled operators or by automated system software".

MATERIALS AND METHODS

Neutron Probe Calibration

To calibrate the neutron probe in Mill Gulch waste rock, we evaluated the response of neutron probe and time domain reflectometry measurements to additions of measured volumes of water to oven dried Mill Gulch waste rock. Neutron probe count ratios were collected for the calibration material at known volumetric moisture contents ranging from the oven dried condition to saturation, yielding a complete calibration relationship. In order to identify the volumetric moisture content at which downward drainage through Mill Gulch waste rock occurs in response to gravity, a drainage system in the calibration apparatus allowed drainage to be observed and measured. Drainage recorded during the laboratory calibration indicated that field capacity for the Mill Gulch waste rock sample studied was five percent volumetric water content. Using this value as an estimate of in situ waste rock field capacity made it possible to identify zones within the repository having volumetric water contents at or above field capacity. Homogeneity of waste rock materials throughout the entire repository was assumed in order to extrapolate the field capacity value and neutron probe calibration to the entire repository.

The primary function of the time domain reflectometry (TDR) measurements was to confirm the critical volumetric water content at which downward drainage occurred in response to gravity by tracking the wetting front through the waste rock. Since TDR has a much faster response time than the drainage system and has adequate spatial resolution to quantify depth profiles of water content, the critical moisture content could be determined more accurately using TDR. Barrel outflow confirmed interpretations of TDR data.

Calibration Material

Fifty gallons of Mill Gulch waste rock having particle sizes ranging from less than 1/16 inch to 6.5 inches in diameter, were used as calibration material. The material was oven dried at 40 degrees Celsius for six weeks. A subsample of the dried material, having a representative range of particle sizes, was oven dried for 48 hours at 105 degrees Celsius, and found to have an initial gravimetric water content of 0.016%. The material was loaded into the 55 gallon barrel in 70 pound increments. Each increment was tamped in order to simulate in situ bulk density. Each waste rock increment had a similar particle size distribution, so as to minimize gradation within the barrel profile. Bulk density analysis of Mill Gulch waste rock revealed that the material had an in situ dry bulk density of 15.40 pounds per gallon (1.85 g/cm^3) before removal from the repository and a repacked dry bulk density of 13.19 pounds per gallon (1.58 g/cm^3) in the calibration barrel.

Instrumentation

Time domain reflectometry probes, a neutron probe access pipe, and a drainage system were installed in a fifty-five gallon PVC drum (Figures 3 and 4).

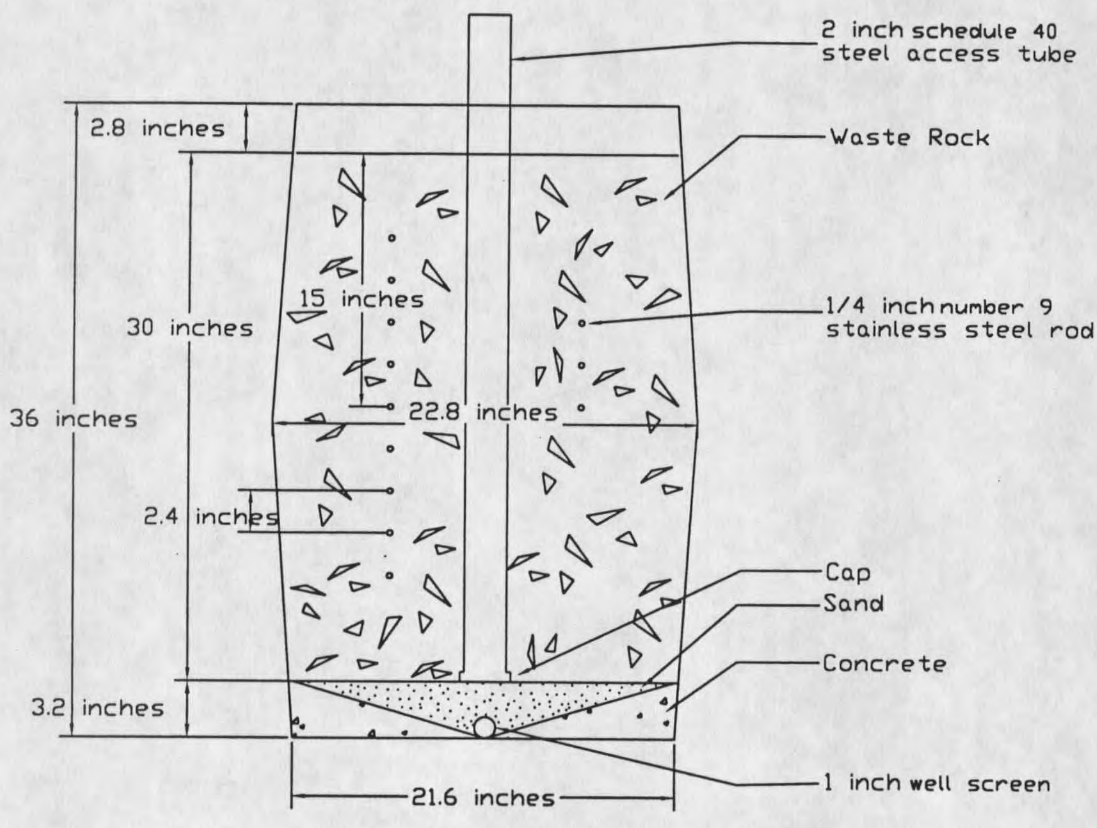

Figure 3. Front view cross section of the calibration apparatus.