AIR INJECTION TO CONTROL OFF-SITE LANDFILL GAS MIGRATION: DESIGN PARAMETERS, MATHEMATICAL MODEL, AND CASE STUDY

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ABSTRACT

Off-site landfill gas (LFG) migration is usually best controlled at its source by installing a collection system in the landfill. If this fails, however, off-site migration can be controlled by intercepting the migration pathways with either passive or active extraction wells and/or trenches. The active systems are normally designed with an exhauster, which pulls LFG through the extraction wells or trenches and either vents it to the atmosphere or sends it to a control device (e.g., a flare). This paper presents an alternative active system design, which utilizes a blower to push air into injection wells, thus cutting off LFG migration pathways with an air barrier.

Although air injection systems have been successfully employed at several sites in the past, the design of these systems typically involves some guesswork on well spacing and system pressure requirements. This paper is intended to advance the industry by providing the design engineer with a basis for establishing these system parameters. Moreover, the paper discusses actions necessary to respond to the discovery of off-site methane migration and the process of selecting the appropriate remediation approach.

A successful air injection case study is presented, including its design, installation, and operation. In the case study, special precaution had to be taken during system startup because improper operation could have lead to methane infiltration into nearby residential homes. The unique procedure developed to control this potential occurrence is presented.

A mathematical model that estimates pressure distribution around injection wells was developed. The model's output compared well with data collected from the case study.

INTRODUCTION

Although one of the less common means of controlling off-site LFG migration, air injection has been successfully employed at numerous facilities across the country. The principle behind air injection systems (also called air curtains or air dikes) is to create a pressure barrier in subsurface soils beyond which migrating LFG cannot pass.

Perhaps the biggest advantage of air injection over LFG extraction is the elimination of a flare (or other control devices) and a condensate management system. Elimination of these components reduces cost, design time, and construction time, and generally makes the system more constructible by ordinary contractors or landfill staff. The cost savings are obvious, since the flare and condensate collection devices are not needed. The schedule is improved because the flare is normally a long lead-time item as is the corrosion resistant coating necessary for blowers that handle LFG. Since air injection system blowers handle fresh air, no such coating is necessary.

Depending on the location of the system (i.e., whether neighbors are close by), the blower equipment may need to be housed in a structure. This represents another advantage in that these air-handling units do not require electrical equipment and installation methods suitable for classified locations as is required by LFG handling equipment when enclosed.

Another important consideration for choosing air injection as a control method is the distance between the air injection wells and the edge of waste. This distance must be sufficient to preclude the introduction of air into the waste mass. The oxygen in the air when in contact with waste can create an aerobic condition leading to a landfill fire. The minimum distance necessary between the wells and edge of waste has been typically quoted as at least 100 feet. However, as this paper will show, the distance is dependent on site geology and system parameters like well flow rate and pressure.

In this paper, a mathematical model is developed for an air injection well that is useful for establishing suitable system design and/or operational parameters (e.g., flow rate, pressure, and well spacing, and distance from edge of waste). The paper also presents an air curtain case study, data from which is used to verify the model.

MATHEMATICAL MODEL

Our mathematical formulation is based on the simplified air injection model presented in Figure 1. Several parameters are introduced in this figure and are defined below:

Q	=	Flow rate into well,
D	=	Depth of well,
H	=	Length of well screen,
r	=	Radial coordinate (centered on the well),
R_w	=	Borehole radius, and
R_I	=	Radius of influence.

We assume that the induced well pressure causes the formation of concentric, cylindrical isobars (i.e., surfaces of equal pressure) centered on the well and that the injected air flows away from the well in a radial manner. Inherent in these assumptions is that the soil is homogeneous and isotropic, yet subsurface air flow is horizontal and does not "short-circuit" to the atmosphere. In addition, gas compressibility is ignored since the pressures applied to the soils are typically relatively low (1 psia range).

Furthermore, assuming that pressure head is the main driving force for movement of the injected air through the soil, we have from Darcy's equation that

$$Q = -KA\frac{d\psi}{dr} \tag{1}$$

where

K	=	Soil permeability with respect to air,
A	=	Cross-sectional area,
ψ	=	Pressure head (P/γ),
P	=	Pressure,
γ	=	Specific weight of air,

and the other parameters are as previously defined. Note that change of velocity and elevation heads with respect to radial distance is negligible and is ignored in Darcy's equation, Eq. [1].

Let's introduce another parameter $\bar{I}$, vertical depth of influence, such that

$$A = 2\pi r\bar{I} \tag{2}$$

Substituting Eq. [2] into Eq. [1], rearranging, and integrating from r_1 to r_2 (where r_2 is greater than r_1), we get

$$\int_{r_1}^{r_2}\frac{dr}{r} = -\frac{2\pi K\bar{I}}{Q}\int_{\psi_1}^{\psi_2} d\psi \tag{3}$$

Carrying out the integration in Eq. [3], we get

$$\psi_1 - \psi_2 = \Delta\psi = \frac{Q}{2\pi K\bar{I}}\ln\left(\frac{r_2}{r_1}\right) \tag{4}$$

Eq. [4] is the general mathematical form of our model. It states that pressure is a logarithmic function of distance from the well, proportional to Q, and inversely proportional to both K and $\bar{I}$.

Eq. [4] is a powerful tool for the design engineer. It tells the story of what happens to the injected air in the subsurface. For a given soil classification (i.e., K), the engineer could use Eq. [4] to select suitable design parameter combinations, i.e., applied pressure/flow rate/well spacing combinations.

Interestingly enough, the mathematical model for an extraction well (installed in soil) under similar assumptions would be the same as Eq. [4], except that ψ would be considered vacuum and Q would be flow rate extracted from the well.

Model Analysis/Parameter Investigation

To help understand our model, let's consider an example. An injection well is installed in soil of uniform profile: 5-foot silty clay, 30-foot sand, and groundwater, top to bottom. The well is installed to groundwater and consists of a 30-foot gravel pack corresponding to the sand layer. (Since we expect that the injected air would move mainly in the more permeable sand layer, $\bar{I}$ would be 30 feet, the depth of the sand layer.) The radius of the well borehole is 6 inches.

In order to investigate well pressures relative to R_I, we will set r_1 at 0.5 feet (radius of the borehole) and r_2 at R_I. Thus, from Eq. [4], we have

$$\Delta\psi = \frac{Q}{2\pi K \bar{I}} \ln(2R_I) \qquad (5)$$

For our example, if Q is set at 30 cubic feet per minute (cfm) and K is assumed to be about 2E-5 feet/sec (fps) for the sand, we calculate the results presented in Figure 2 (the middle curve, sand).

For example, it is estimated using Figure 2 that an applied pressure of about 8 inches of water column (in.-wc) (i.e., the pressure applied to the gravel pack) should cause a radius of influence of about 30 feet.

Figure 2 also plots curves for other typical soil types or permeabilities: silty sand (K of 2E-6 fps) and gravel (K of 2E-3 fps). (Refer to Table 1 for permeability values of various soil types.) Note that as K varies by orders of magnitude, $\Delta\psi$ also varies by orders of magnitude. These curves suggest that the air injection technology becomes less attractive for soils of low permeability (silt to clay range), due to the high pressure requirements.

TABLE 1. PERMEABILITY VALUES

Soil Type	Range* (Darcy)	Typical (Darcy)	Typical Air** Permeability (fps)
Gravel	1E2—1E5	1E3	2E-3
Sand	5E-1—1E3	10	2E-5
Silty Sand	1E-2—1E2	1	2E-6
Silt	1E-4—1	1E-3	2E-9

*Freeze and Cherry, 1979

**Based on air at 20° Celsius or 68° Fahrenheit

Care should be used when interpreting the results of the model. For example, Figure 2 suggests that for gravel R_I has the potential to be much greater than 100 feet for only a slight increase of pressure, less than 1 in.-wc. This would be valid only if there exists an ideal case that perfectly fits our model assumptions. Consideration should be given to real situations such as atmospheric short-circuiting, the magnitude of static subsurface pressure gradient (that contributes to LFG movement), preferential movement, and other geological complexities that may exist, and adjustments should be made as appropriate.

Solving Eq. [5] for R_I, we get

$$R_I = R_w \exp\left(\frac{2\pi K \bar{I} \Delta\psi}{Q}\right) \qquad (6)$$

where we have reintroduced r_1, setting it equal to R_w. From Eq. [6], we observe that R_I is directly proportional to R_w, neglecting the head losses that occur inside the gravel pack. Thus, a 12-inch diameter well will have twice as much influence as a 6-inch diameter well.

Eq. [6] also states that R_I would be larger in higher-permeability soils. In addition, R_I would increase for higher pressures and lower flow rates, provided $\bar{I}$ remains the same. This situation is further discussed in the case study below.

CASE STUDY

Background

The Eastern Sanitary Landfill in Baltimore County is a 200-acre facility that presently has approximately 3:8 million tons of waste in place. Refer to Figure 3, Site Map. The facility opened in 1982 and the initial cells were constructed with a bentonite bottom liner and Hypalon liner on the cut side slopes. Off-site methane migration was detected in 1994 adjacent to one of the earlier cells, Phase II. A buffer of woods exists between the edge of waste and a residential road (Loreley Beach Road) across which several homes are located. Refer to Figure 4.

Migration was initially detected in monitoring probes located near the base of the landfill. Additional probes were installed between the monitoring wells and the edge of Loreley Beach Road. When these additional probes were found to contain methane concentrations exceeding 5%, several probes were installed in the yards of the homes across the road. Concurrent with the installations of these additional probes, the basements of these homes were monitored for methane. No methane was detected in the homes; however, methane concentrations exceeded 40% in several of the probes located on the residential property.

Design, Installation, and Operation

Numerous conditions at this particular site warranted consideration of an air curtain. Specifically, the following factors lead to selection of this type of system:

- Installation of the system would need to be in the soil between the landfill and Loreley Beach Road to intercept the migrating LFG. This area was mostly wooded and limited space was available for a control device such as a flare, which would have required significant clearing of trees.
- Schedule was important; therefore, the previously mentioned schedule advantages of the air curtain were critical.
- Since no emissions are associated with the air curtain, the need for an air permit and the corresponding schedule delays were eliminated.

- Noise was also a consideration and air-handling blowers could be housed in a small precast concrete building with no external equipment.

- As with every project, budget was a consideration. The lack of a flare or other control device coupled with the use of schedule 40 PVC piping and other off-the-shelf components enabled local plumbing contractors to respond to the request for bids.

The extent of the migration was well defined by the numerous monitoring probes. Therefore, the length of the air curtain was readily established based on the monitoring data. The depths of the air injection wells were limited by the depth to groundwater, which varied from 10 to 35 feet below grade. The control valves for the injection wells were housed in hand holes buried at grade to minimize the potential for tampering. Because no 3-phase power was available, two 5 hp blowers were employed to attain the desired pressure and flow.

The design of the blower station, piping and valves enabled temporary operations in the extraction mode during start-up of the system. This was an important aspect of the project since methane migration had already occurred beyond the system. If initial operations were in the injection mode, the methane already in the ground would have been pushed towards the homes.

Startup involved approximately one week of extraction of subsurface gases. These were vented to the atmosphere through a temporary exhaust stack. Extraction of the gas was conducted until the methane was removed from the probes in the residential yards and from the probes nearest Loreley Beach Road (on the landfill side). Once these probes were clean, air injection commenced. Since operating in the injection mode, the monitoring probes have remained clean.

Landfill staff operates and maintains the system. The system has been nearly trouble free except for one instance when water got into the header piping after an unprecedented duration of heavy rains and simultaneous power outage. At that time, it was necessary to pump water out of the header using a small portable pump to clear the lines.

Monitoring the system can be done remotely via a telephone dialer that enunciates the system status. The dialer also enables the caller to listen to sounds within the building, which provides a positive indication that the blower equipment is operating.

Field Data Comparison to Model

Field data was collected during system startup. Our analysis here will focus around well W-2, due to the good population of probes in this area (refer to Figure 4). Table 2 presents monitoring data for four monitoring events.

The soil profile in the vicinity of W-2 and the nearby probes is presented in Figure 5. This profile is based on the well/probe drill logs; the groundwater elevation is approximated from well data in the nearby area.

TABLE 2. FIELD DATA

Date	Probe P-35B (in.-wc)	Probe P-27 (in.-wc)	Probe P-35A (in.-wc)	Well * W-2 (cfm)
7/7/97	2.0	1.7	0	
	3.2	2.5	0	34
7/9/97	3.1	2.3	0	38
	5.0	3.9	0	

* Approximate flow based on measured flow rate at the blower and flow ratios recorded during system balancing

As seen in Figure 5, the soil profile basically consists of a silt layer over a sand layer, except for around P-35A. At P-35A, there also exists a sand layer in the uppermost region of the profile. The profile suggests that the flow pathways of injected air would be mainly in the sand layer between the silt layer and the groundwater, which is about 30 feet deep on average. In addition, it suggests that the injected air may not directly influence P-35A, which is confirmed by the field data (pressure measurements) listed in Table 2.

Based on the field data and site geology, ψ, r, and $\bar{l}$ in Eq. [4] are either known or can be approximated. The unknown variables are K and Q, although we do have a "ballpark" estimate for Q. Table 3 presents results of an error analysis that found the best fit for these variables. These results only consider P-35B and P-27 since, as mentioned, we believe that the injected air did not directly influence P-35A. The distances of P-35B and P-27 relative to W-2 are 5 feet and 14 feet, respectively (refer to Figure 5). $\bar{l}$ was assumed to be 30 feet, the average depth of the sand layer over the groundwater.

TABLE 3. BEST-FIT RESULTS

Date	$\Delta\psi$ (in.-wc)	K (fps)	Q (cfm)
7/7/97	0.3	4E-3	15
	0.7	4E-3	35
7/9/97	0.8	4E-3	41
	1.1	4E-3	56

As shown in Table 3, the best-fit estimate for K is 4E-3 fps. The table also shows best-fit estimates for Q for the four monitoring events: notice that they correspond well with the field data estimates in Table 2.

The best-fit curves and actual data points are plotted in Figure 6 for the four monitoring events: almost perfect fits are indicated. It is interesting to note that the low-pressure/low-flow curve (bottom curve) indicates that these pressure/flow settings can cause a larger radius of influence (assuming that the static subsurface pressure gradient contributing to LFG movement is negligible). This is the case if the depth of influence, $\bar{l}$, remains the same as pressure and flow changes, as we have assumed here. (It is analogous to pipe flow: head loss decreases with decreasing flow and increasing diameter and vice visa.) However, if $\bar{l}$ also changes such that it decreased for decreasing well pressure, the radius of influence will also decrease, in accordance with the model. This scenario was not investigated here, due to limited field data.

REFERENCES

Freeze, R. A., and Cherry, J. A., 1979, Groundwater, Prentice Hall, Englewood Cliffs, NJ, Ch. 2, p. 29.

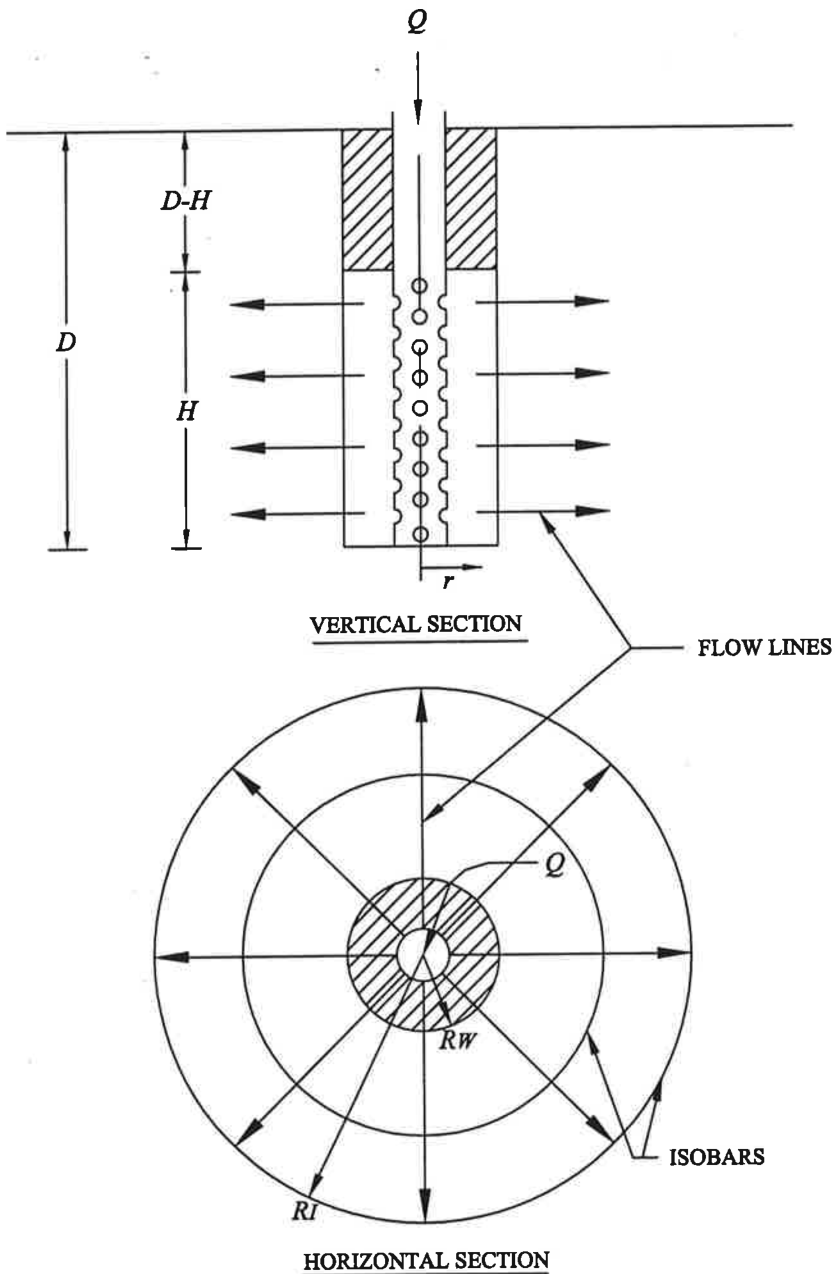

FIGURE 1. AIR INJECTION MODEL

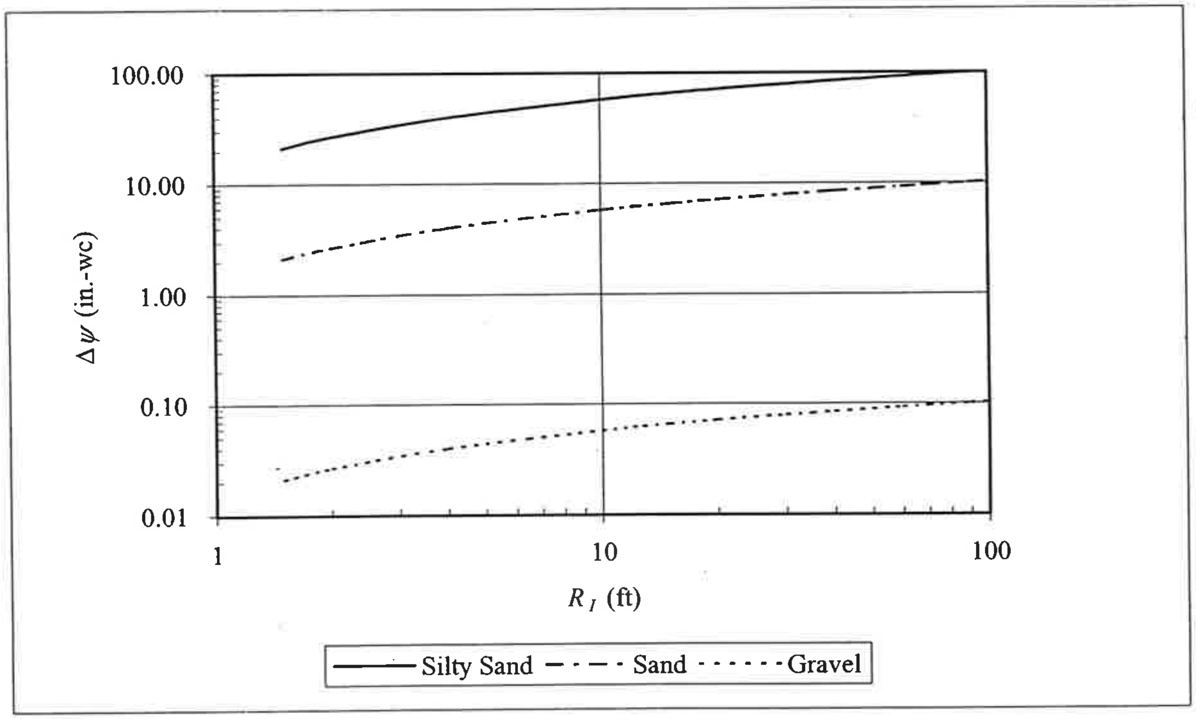

FIGURE 2. $\Delta\psi$ VERSUS R_I FOR TYPICAL SOIL TYPES

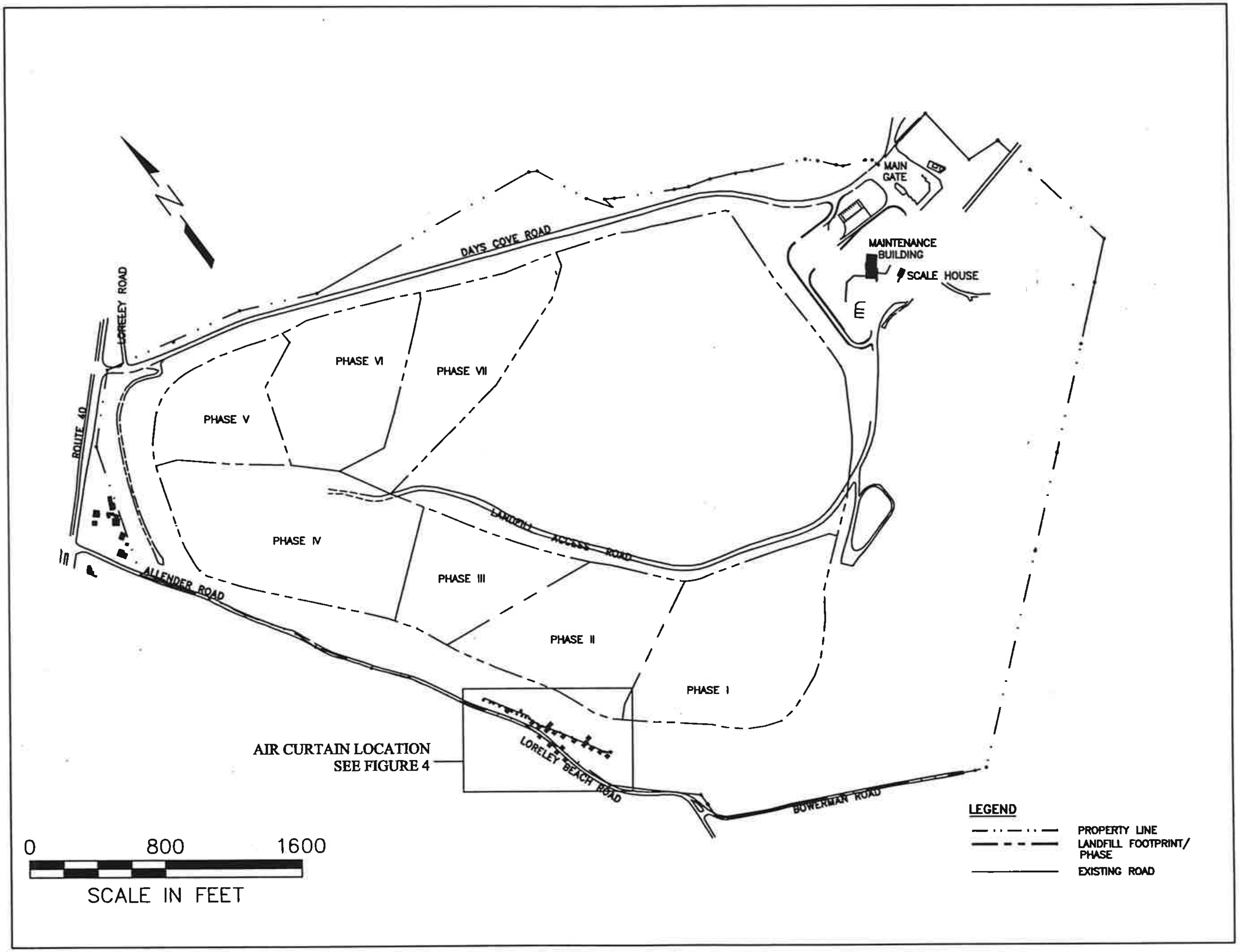

FIGURE 3. SITE MAP

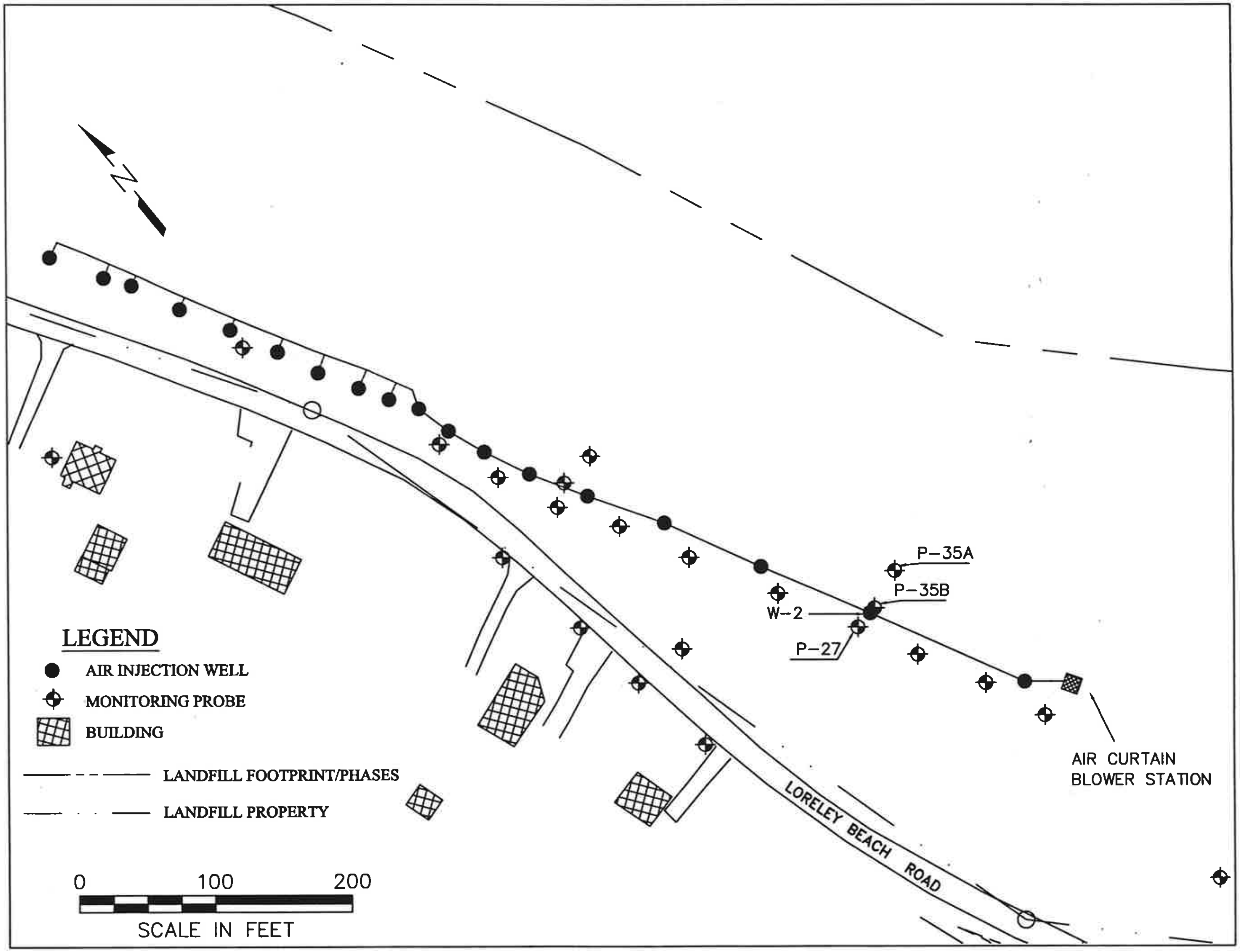

FIGURE 4. AIR CURTAIN LAYOUT

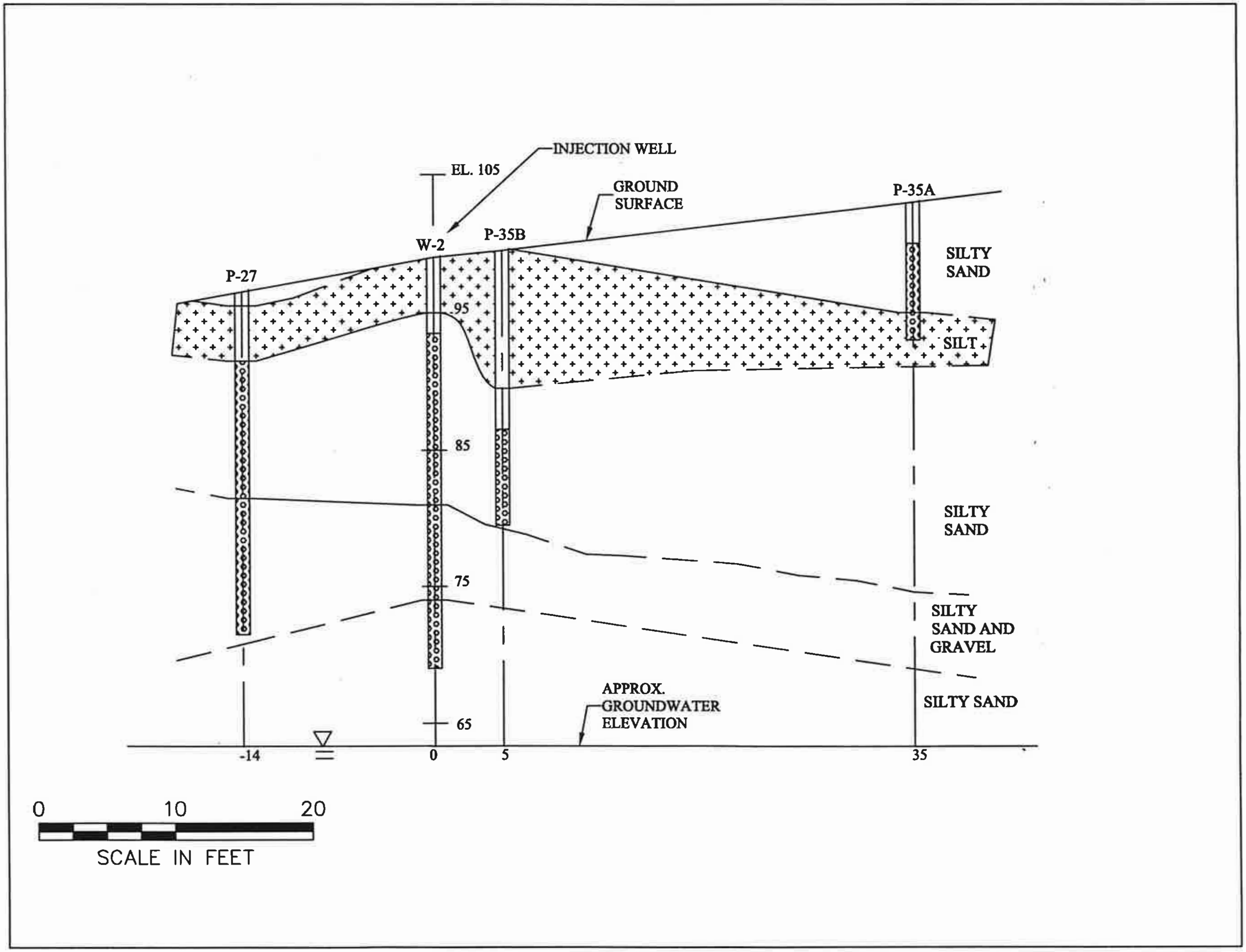

FIGURE 5. SOIL PROFILE IN THE VICINITY OF INJECTION WELL W-2

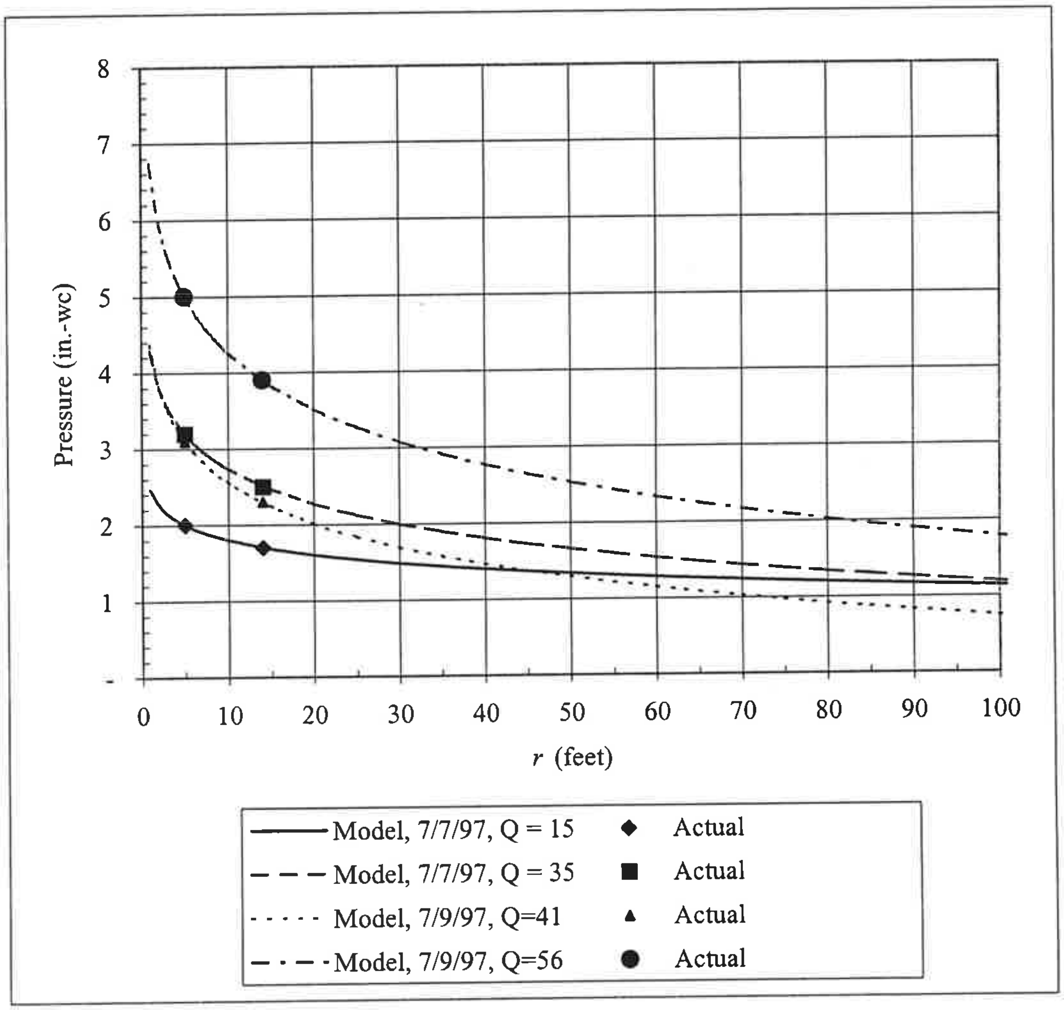

FIGURE 6. COMPARISON OF MODEL AND ACTUAL DATA