Design and Construction of Cantilevered Retaining Walls

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Abstract: The purpose of this paper is to describe the design and construction of reinforced cantilevered retaining walls. Two case studies of retaining wall failures are presented. For the first case, the wall failed as a result of a reduction in lateral support. In the second case, the wall was damaged as a result of the increase in lateral pressure from the Northridge earthquake. A cantilevered retaining wall must have an adequate factor of safety for sliding and overturning, and have a footing bearing pressure less than the allowable bearing pressure. Two other common reasons for the failure of cantilevered retaining walls are using on-site soil and generating excess pressures during backfill compaction. Using on-site soil may lead to failure because the soil may not have the shear strength or permeability properties assumed during the wall design stage. To prevent damage to the wall from excess compaction pressures, lightweight hand-operated equipment or bobcats should be used for backfill compaction.

INTRODUCTION

A retaining wall is defined as a structure whose primary purpose is to provide lateral support for soil or rock. In some cases, the retaining wall may also support vertical loads. Examples include basement walls and certain types of bridge abutments.

Cernica (1995) lists and describes various types of retaining walls. Some of the more common types are gravity, counterfort, and cantilevered walls. Gravity retaining walls are routinely built of plane concrete or stone, and the wall depends primarily on its massive weight to resist failure from overturning and sliding. Counterfort walls consist of a footing, a wall stem, and intermittent vertical ribs (called counterforts) that tie the footing and wall stem together.

Although reinforced earth-retaining walls have become more popular in the past decade, cantilever retaining walls are still probably the most common type of retaining structure. There are many different types of cantilevered walls, with the common feature being a footing that supports the vertical wall stem. Typical cantilevered walls are T-shaped, L-shaped, or reverse L-shaped (Cernica 1995).

To prevent the buildup of hydrostatic water pressure on the retaining wall, clean granular material (no silt or clay) is the standard recommendation for backfill material. Import granular backfill generally has a more predictable behavior in terms of earth pressure exerted on the wall. A backdrain system is often constructed at the heel of the wall to intercept and dispose of any water seepage in the granular backfill.

The purpose of this paper is to describe the design and construction of reinforced cantilevered retaining walls. Two examples of retaining wall failures are presented first.

CASE STUDIES

Case Study 1—Reduction in Lateral Support

The first case study involves a retaining wall failure in San Diego, Calif. The wall was constructed as a basement wall for a large building. In 1984, the building was demolished and the site was turned into a parking lot.

As originally constructed, the basement wall received lateral support from the foundation, a bowstring roof truss, and perpendicular building walls. When the building was demolished, essentially the retaining wall became a cantilevered wall with no lateral support except from the footing.

The retaining wall is about 2.4–2.7 m (8–9 ft) high, 20 cm (8 in.) thick, with thickened pilasters that originally supported the bowstring roof truss. Fig. 1 shows a photograph of the wall after demolition of the building. The area behind the wall belonged to an adjacent property owner, who experienced damage when the wall moved as a result of the loss of lateral support. Fig. 2 shows a photograph of cracks that opened up in the concrete flatwork located behind the retaining wall.

The movement of the wall was monitored by installing brass pins on opposite sides of the flatwork cracks. By measuring the distance between the pins, the opening of the cracks (lateral movement) was calculated and plotted versus time as shown in Fig. 3. The horizontal axis in Fig. 3 is time after installation of the pins.

In Fig. 3 the movement of the wall versus time is not a constant rate, but rather intermittent. The data indicates that the wall moves forward, the cracks open up, and then lateral movement ceases for a while. This is because the soil thrust is reduced when the wall moves forward, and it takes time for the soil to reassume its original contact with the back face of the wall. In Fig. 3, crack pin (CP) number 3 did record a closing of the crack at a time of 0.9–1.2 years, but this is because of settling of the backfill and flatwork as the soil reassumed contact with the back face of the wall. Fig. 4 shows the voids that developed beneath the flatwork due to lateral movement of the wall.

Case Study 2—Earthquake Loads

As illustrated by case study 1, most retaining wall failures are gradual, and the wall fails slowly by intermittently tilting or moving laterally. It is possible that a failure can occur suddenly, such as when there is a slope-type failure beneath the wall or when the foundation of the wall fails because of inadequate bearing capacity. These rapid failure conditions can develop when the wall foundation is supported by clay (Cernica 1995).

Another example of sudden wall failure could occur during an earthquake. It is difficult to predict accurately the additional lateral forces that will be generated on a retaining wall during an earthquake. Some factors affecting the magnitude of earthquake forces on the wall are the size and duration of the earthquake, the distance from the earthquake epicenter to the site, and the mass of soil retained by the wall. Many retaining walls are designed only for the active earth pressure and then fail when additional forces are generated by the earthquake. Methods to include earthquake forces in retaining wall design are shown in NAVFAC DM 7.2 (1982), on page 7.2–78.

The second case study involves retaining wall damage caused by the January 17, 1994 Northridge earthquake (mag-

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Note. Discussion open until July 1, 1997. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on May 22, 1996. This paper is part of the ***Practice Periodical on Structural Design and Construction***, Vol. 2, No. 1, February, 1997. ©ASCE, ISSN 1084-0680/97/0001-0016–0021/$4.00 + $.50 per page. Paper No. 13289.

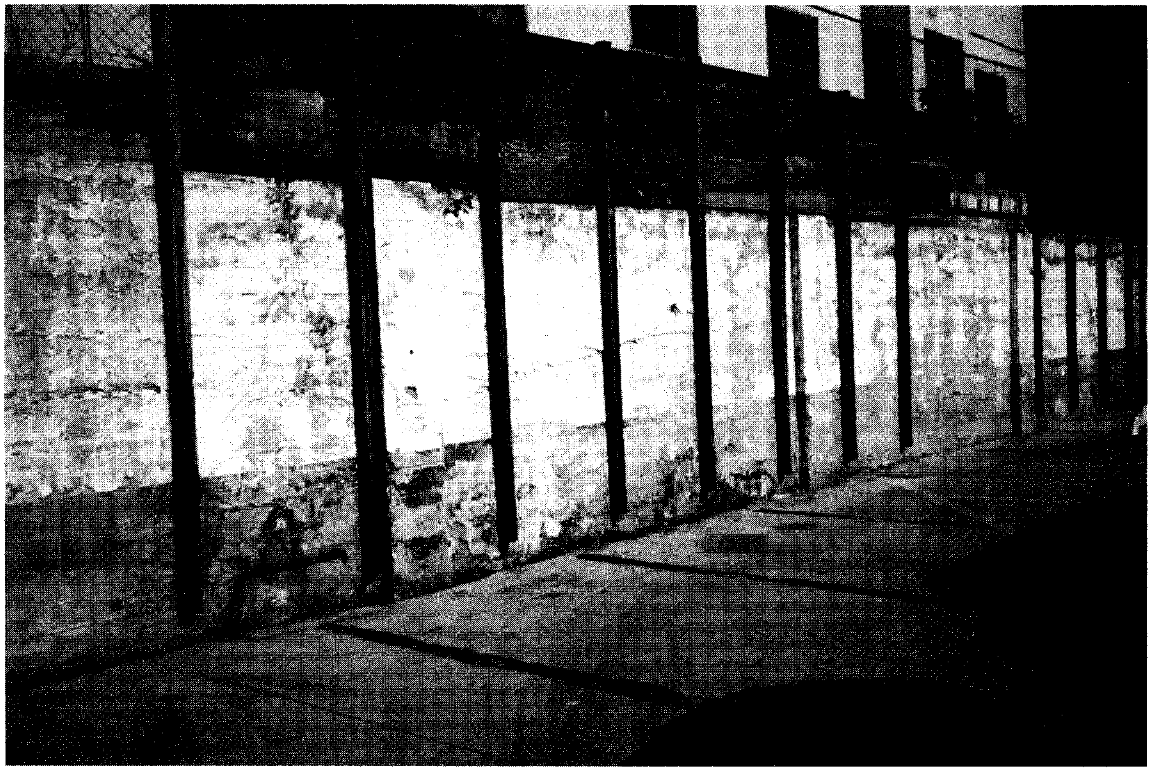

FIG. 1. Cantilevered Retaining Wall

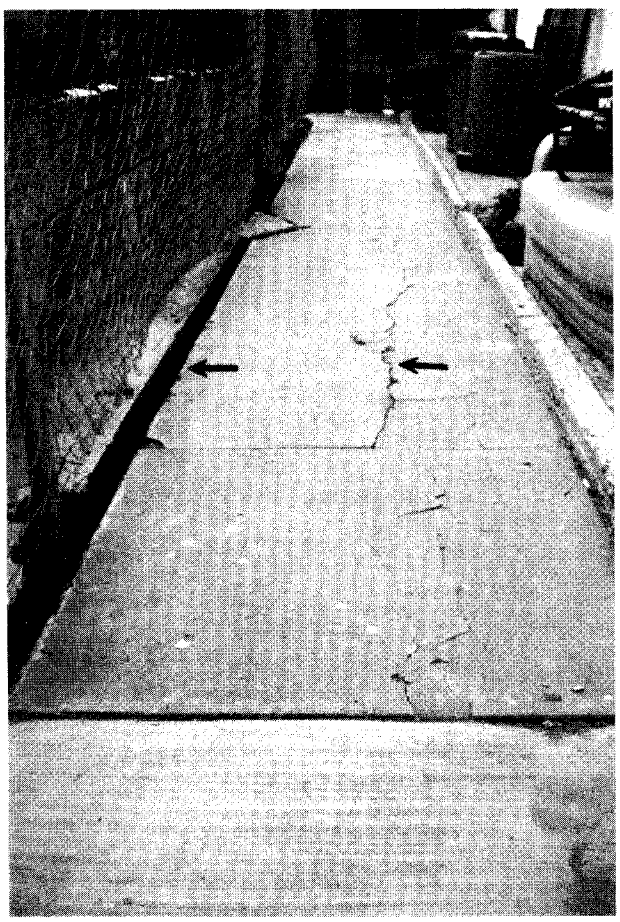

FIG. 2. Area behind Retaining Wall (Arrows Point to Cracks Opening up in Flatwork)

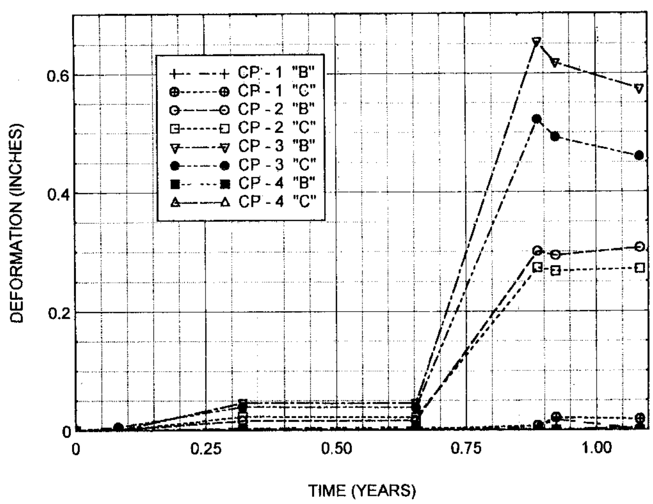

FIG. 3. Wall Deformation versus Time

nitude = 6.7) in California. The site is located about 13 km (8 mi) southwest of the epicenter of the Northridge earthquake. The EQSEARCH (Blake 1989) computer program was used to estimate the peak ground acceleration at the site during the Northridge earthquake. This computer program obtains the peak ground acceleration by using the Joyner and Boore (1982) attenuation relationship. According to the computer program, the estimated peak ground acceleration at the site was 0.51 *g*.

Fig. 5 shows a cross section through the house. A retaining wall was constructed near the top of the slope. The house was then built in front of the wall. The house provided lateral support for a portion of the retaining wall and this portion did not sustain any damage during the Northridge earthquake. However, the portion of the retaining wall that did not receive

FIG. 4. Voids that Developed below Flatwork as Result of Wall Movement

support from the house experienced cracking and tilting during the Northridge earthquake. Fig. 6 shows typical earthquake damage to the retaining wall.

Besides cracking and tilting of the retaining wall, it was also observed that the backfill settled during the Northridge earthquake. Fig. 7 shows the settlement of the sidewalk and asphalt driveway that was supported by the wall backfill. Fig. 5 shows the location of Fig. 7. The affect of the Northridge earthquake was to densify the backfill and increase the lateral pressure that caused damage to the portion of the retaining wall not receiving lateral support from the house.

DESIGN OF CANTILEVERED RETAINING WALLS

Active Earth Pressure

Fig. 8 shows a reverse L-shaped cantilever retaining wall. The pressure exerted on the wall is the active earth pressure. The footing is supported by the vertical bearing presure of the soil or rock. Lateral movement of the wall is resisted by passive earth pressure and slide friction between the footing and bearing material.

As shown in Fig. 8, the active earth pressure is generally assumed to be horizontal because the friction developed between the vertical wall stem and the backfill is neglected. This friction force has a stabilizing effect on the wall, and therefore it is a safe assumption to ignore friction. In the evaluation of the active earth pressure, it is common for the soil engineer to recommend clean granular soil as backfill material. In order to calculate the active earth pressure resultant force (P_a), in kN/m of wall or lb/ft of wall, the following equation is used for clean granular backfill:

$$P_a = (1/2)k_a\gamma_t H^2 \tag{1}$$

where k_a = active earth pressure coefficient; γ_t = total unit weight of the backfill; and H = height over which the active earth pressure acts as defined in Fig. 8. The active earth pressure coefficient (k_a) is equal to

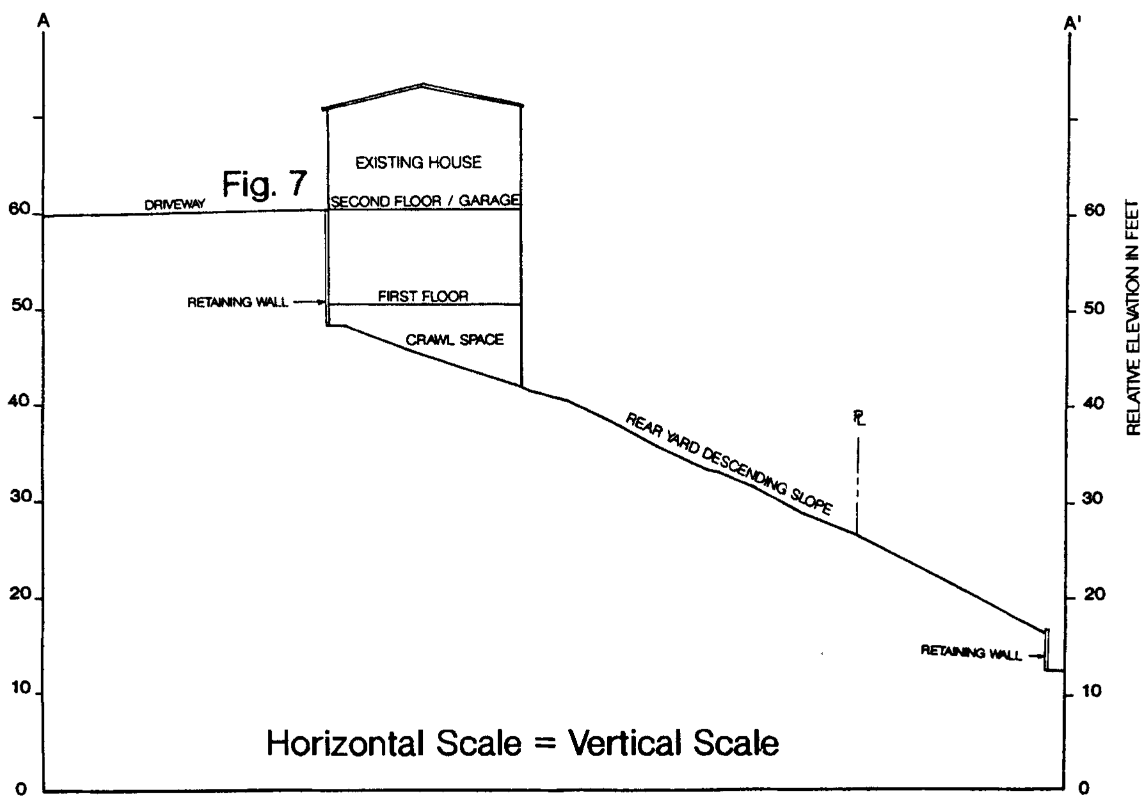

FIG. 5. Cross Section through House

FIG. 6. Earthquake Damage to Retaining Wall

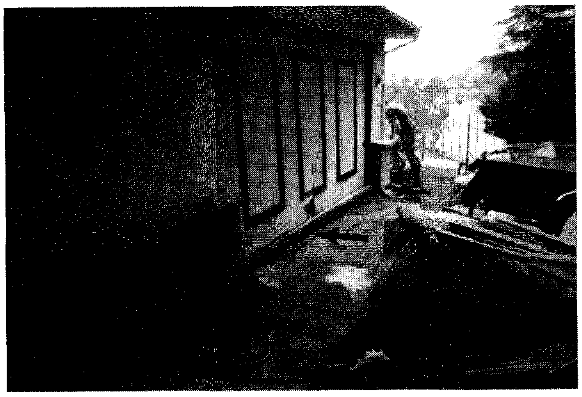

FIG. 7. Backfill Settlement as Result of Northridge Earthquake

$$k_a = \tan^2[45 - (1/2)\phi] \quad (2)$$

where ϕ = friction angle of the clean granular backfill.

In (1) the product of k_a times γ_t is referred to as the equivalent fluid pressure. In the design analysis, the soil engineer usually assumes a total unit weight (γ_t) of 19 kN/m^3 (120 pcf) and a friction angle (ϕ) of 30° for the granular backfill. Using (2) and ϕ = 30°, the active earth pressure coefficient (k_a) is 0.333. Multiplying 0.333 times the total unit weight (γ_t) of backfill results in an equivalent fluid pressure of 6.3 kN/m^3 (40 pcf).

This is the typical recommendation for equivalent fluid pressure from soil engineers. It is valid for the conditions of clean granular backfill, a level ground surface behind the wall, a backdrain system, and no surcharge loads. Note that this commonly recommended value of equivalent fluid pressure of 6.3 kN/m^3 (40 pcf) does not include a factor of safety and is the actual pressure that would be exerted on a smooth wall when the friction angle (ϕ) of the granular backfill equals 30°. When designing the vertical wall stem in terms of wall thickness and the size and location of steel reinforcement, a factor of safety (F) can be applied to the active earth pressure in (1). A factor of safety may be prudent because higher wall pressures will most likely be generated during compaction of the backfill or when translation of the footing is restricted (Day 1995; Goh 1993).

For the case of an inclined slope behind the retaining wall, equations and tables have been developed to determine the active earth pressure coefficient (k_a) (Dept. of the Navy 1982, p. 7.2–64). If there is a uniform surcharge pressure (Q) acting on the ground surface behind the wall, then there would be an additional horizontal pressure exerted upon the retaining wall equal to the product of k_a times Q.

Allowable Passive Earth Pressure

To develop passive pressure, the wall footing must move laterally into the soil. As indicated in Table 1 (Dept. of the Navy 1982), the wall translation to reach the passive state is at least twice that required to reach the active earth pressure state.

Usually it is desirable to limit the amount of wall translation by applying a reduction factor to the passive pressure. A commonly used reduction factor is 2.0 (Lambe and Whitman 1969). The soil engineer routinely reduces the passive pressure by 1/2 (reduction factor = 2.0) and then refers to the value as the allowable passive pressure. To limit wall translation, the structural engineer should always use the allowable passive pressure for design of the retaining wall.

The passive pressure may also be limited by building codes. For example, the allowable passive soil pressure, in terms of equivalent fluid pressure, is 16 to 32 kN/m^3 (100–200 pcf) per the Uniform Building Code (1994).

Bearing Pressure

To calculate the footing bearing pressure, the first step is to sum the vertical loads, such as the wall and footing weights. The vertical loads can be represented by a single resultant vertical force (W), per linear meter or foot of wall, that is offset by a distance (x') from the toe of the footing. The resultant force (W) and the distance x' can then be converted to a pressure distribution as shown in Fig. 8 [see Lambe and Whitman (1969), Example 13.12]. The largest bearing pressure is routinely at the toe of the footing (point A, Fig. 8). The largest bearing pressure should not exceed the allowable bearing pressure, which is usually provided by the soil engineer or by local building code specifications.

Factor of Safety for Sliding

The factor of safety (F) for sliding of the retaining wall is defined as the resisting forces divided by the driving force. The forces are per linear meter or foot of wall, or

$$F = \frac{\text{Sliding Friction Force + Allowable Passive Resultant Force}}{\text{Active Earth Pressure Resultant Force}}$$

$$= \frac{\mu W + P_p}{P_a} \quad (3)$$

where μ = friction coefficient between the concrete foundation and bearing soil; W = resultant vertical force; P_p = passive resultant force; and P_a = active earth resultant force calculated from (1). The typical recommendations for minimum factor of safety for sliding is 1.5 to 2.0 (Cernica 1995).

In some situations, there may be adhesion between the bottom of the footing and the bearing soil. This adhesion should be neglected because the wall is designed for active pressures, which typically develop when there is translation of the footing. Translation of the footing will break the adhesive forces between the bottom of the footing and the bearing soil and therefore adhesion should be neglected for the factor of safety for sliding.

Factor of Safety for Overturning

The factor of safety (F) for overturning of the retaining wall is calculated by taking moments about the toe of the footing (point A, Fig. 8), and is

$$F = \frac{\text{Stabilizing Moment}}{\text{Overturning Moment}} = \frac{Wx'}{(1/3)P_aH} \quad (4)$$

where x' = distance from the resultant vertical force (W) to

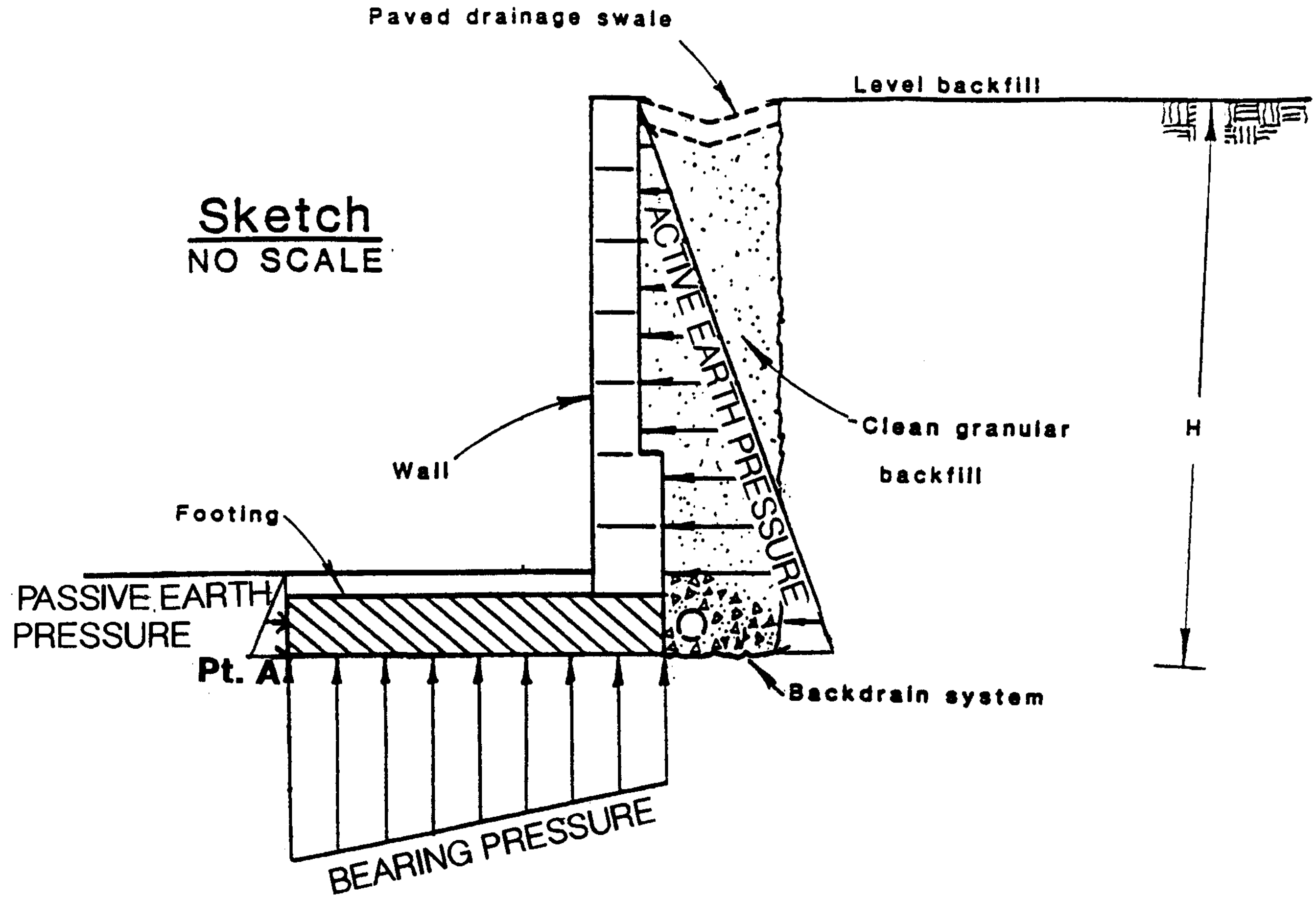

FIG. 8. Retaining Wall-Design Pressures

TABLE 1. Magnitudes of Wall Rotation to Reach Failure

Soil type and condition (1)	Rotation Y^a/H^b Active (2)	Passive (3)
Dense cohesionless	0.0005	0.002
Loose cohesionless	0.002	0.006
Stiff cohesive	0.01	0.02
Soft cohesive	0.02	0.04

[a]Y = Horizontal displacement.
[b]H = Height of the wall.

the toe of the footing; and P_a = active earth resultant force calculated from (1). The typical recommendations for minimum factor of safety for overturning is 1.5–2.0 (Cernica 1995).

BACKFILL MATERIAL FOR CANTILEVERED RETAINING WALLS

There are many different aspects to the construction of cantilevered retaining walls. The purpose of this section is not to cover all of those construction details, but rather to focus on the backfill material, which is a frequent cause of failure for cantilevered retaining walls.

Type of Backfill Material

As previously mentioned, clean granular sand or gravel should be used as backfill material. This is because of the undesirable effects of using clay or silt as a backfill material. When clay is used as backfill material, the clay backfill can exert swelling pressures on the wall (Day 1993; Marsh and Walsh 1996). The highest swelling pressures develop when water infiltrates a backfill consisting of a clay that was compacted to a high dry density at a low moisture content. The type of clay particles that will exert the highest swelling pressures are montmorillonite.

Another problem with clay backfill is that it will not be free-draining, which could result in hydrostatic forces or ice-related forces that substantially increase the thrust on the wall.

To reduce construction costs, soil available at the site is sometimes used for backfill. This soil may not have the properties, such as being a clean granular soil with a high shear strength, that was assumed during the design stage. Using on-site available soil, rather than importing granular material, is probably the most common reason for retaining wall failures.

The vertical back-cut shown in Fig. 8 should only be used

FIG. 9. Back-Cut Slope for Retaining Wall Construction

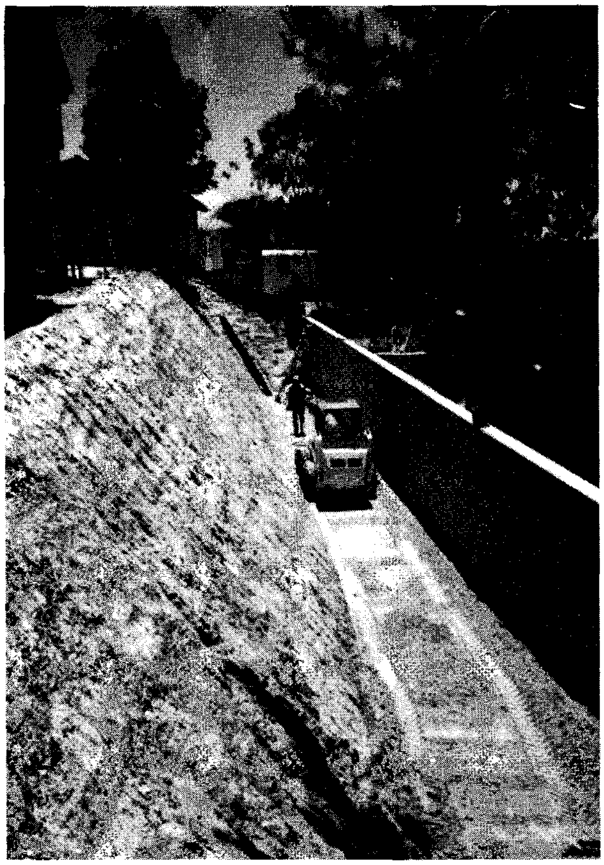

FIG. 10. Compaction of Backfill

when the retaining wall is less than 1.5 m (5 ft) high. In all other cases, the back-cut should be sloped. The back-cut slope inclination can be determined from slope stability analysis, but should not be steeper than 0.75:1.0 (horizontal:vertical). Fig. 9 shows an example of the back-cut slope for the construction of a retaining wall in San Carlos, Calif.

Compaction of Backfill Material

As previously mentioned, one reason for applying a factor of safety (F) to the active earth pressure [(1)] is that larger wall pressures will typically be generated during compaction of the backfill. By using heavy compaction equipment in close proximity to the wall, excessive pressures can be developed that damage the wall. The best compaction equipment in terms of exerting the least compaction-induced pressures on the wall, are small vibrator plate (hand-operated) compactors such as models VPG 160B and BP 19/75 (Day 1993; Duncan et al. 1991). The vibrator plates effectively densify the granular backfill, but do not induce high lateral loads because of their light weight.

Besides hand-operated compactors, other types of relatively lightweight equipment can be used to compact the backfill. For example, Fig. 10 shows a bobcat being used to place and compact the backfill.

CONCLUSIONS

The purpose of this paper is to describe the design and construction of cantilevered retaining walls. As shown in Fig. 8, there are three different pressures acting on cantilevered retaining walls: active earth pressure, passive pressure, and footing bearing pressure. The cantilevered retaining wall must have an adequate factor of safety for failure as a result of sliding and overturning, and must have a footing bearing pressure less than the allowable bearing pressure.

As illustrated by case study 1, most retaining wall failures are gradual; the wall slowly fails by intermittently tilting or moving laterally (Fig. 3). Common reasons for cantilevered retaining wall failures are due to a reduction in wall support (case study 1) or additional loads, such as from earthquakes (case study 2).

Cantilevered retaining walls are usually designed assuming granular import backfill. Another common reason for the failure of cantilevered retaining walls is because the on-site soil is used as backfill. The on-site soil may not have the shear strength or permeability requirements that were assumed during the design stage. Retaining walls can also be damaged by excess pressures generated during the compaction of the backfill. Lightweight hand-operated compactors or bobcats should be used, as shown in Fig. 10.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

- F = factor of safety;
- H = height over which active earth pressure acts;
- k_a = active earth pressure coefficient;
- P_a = active earth resultant force, per linear meter or foot of wall;
- P_p = passive earth resultant force, per linear meter or foot of wall;
- W = resultant of vertical wall loads, per linear meter or foot of wall;
- x' = distance from W to toe of footing;
- γ_t = total unit weight of backfill;
- μ = friction coefficient between concrete foundation and bearing soil; and
- ϕ = friction angle of clean granular backfill.