REMR Technical Note GT-RE-1.5

Physical Modeling: Principles Applied to Sliding Stability of Gravity Structures

Purpose

The purpose of this technical note is to document a method for evaluating sliding stability of gravity structures using physical modeling.

Application

The main loadings on gravity structures are produced by body forces generated by the action of gravity on water, soil, and rock. The stresses within gravity structures are produced by the combination of self-weight of the structure and body force loadings of water, soil, and rock. A small model of a full-size structure (prototype) can be used to make inferences regarding the full-size structure if similitude can be maintained in the testing of the model.

Background

Civil works are one-of-kind items that cannot be tested to failure. Full-scale testing may also be dangerous or impractical. Modeling to evaluate sliding stability is possible, but rarely used. Conversely, hydraulic modeling is well-established as a component of design and has been used to evaluate the design of channels, gates, orifices, and the like, where analysis procedures are not well developed or significant factors are neglected for ease of computation. Testing to evaluate the stability and behavior of gravity structures is feasible under certain conditions. Geometric and, in some cases, dynamic similitude must be maintained to experimentally evaluate the suitability of a design.

Advantage

Physical modeling can be used to realistically evaluate three-dimensional (3-D) attributes such as geologic features and changes in the geometry of the structure. The model may be tested to failure, if desired. The kinematics of failure can be observed, and the effects of geologic features can be assessed.

Requirements

The model components must satisfy geometric similitude with the prototype. Dynamic similitude may also be required depending on the nature of the prototype components and loading conditions.

Geometric similitude

The dimensions of the model are a consistent fraction of the prototype dimensions. A 1:n model will be such that the coordinates of features in the model are the prototype coordinates divided by n.

Dynamic similitude

Given that a model is built to satisfy geometric similitude, the dynamic parameters must be controlled to ensure realistic behavior. For fluids, the dynamic parameters are viscosity, density, velocity, and pressure. These parameters contain one or more units of mass, force, and time. Dynamic similitude is maintained by considering one or more well-known dimensionless parameters such as Reynold's number or Froude number. All of the dimensionless parameters pertaining to fluid dynamics contain a velocity term. If velocities are near zero, as is often the case in flow through soil, dynamic similitude may be unimportant.

Model properties

The materials used to model the structure and its foundation must have moduli and strengths scaled to maintain similitude. Simulant materials will be required that can be designed to have stiffness and strength reduced to maintain proper relationships among the important parameters. In general, these materials must be at least an order of magnitude less stiff and less strong than the materials in the prototype.

Limitations

Usually it is impossible to maintain complete similitude. When similitude is compromised, additional experiments should be performed to evaluate the influence of these departures from similitude. The process of additional testing to evaluate the effects of compromises in similitude is called modeling of models.

Boundary conditions of the entire model as a package can limit the applicability of the test results. The boundary is the interface between the model and the container holding the model. The boundary conditions include physical restrictions (container walls and base), confinement changes (container stiffness, side friction), and container-model interaction. Modeling of models can be used to evaluate these effects, but the cost and time required to fully evaluate these conditions can become large.

Rock and soil have attributes that are difficult to model. Soil is a particulate media, so the strength, permeability, grain-size distribution, and compressibility are interrelated. Usually geometric similitude of the grain size is violated to attempt to retain proper scaling of strength and compressibility.

Rock contains fractures, bedding planes, and other inhomogeneities that dominate the behavior of the rock. These features have attributes of orientation, crack width, roughness, waviness, and persistence that are extremely difficult to model at reduced scale. In theory, modeling of models can be used to assess the relative importance of maintaining similitude in these attributes. In practice, it is impossible to create an accurate model of these features in a small model. Research is needed to document the consequences of neglecting these features.

Similitude Summary

A list of scaling factors is shown in Table 1. Each factor is a ratio of a prototype attribute to a model attribute. The table applies to models having a scale of 1:n to the prototype. The parameters are those used to evaluate sliding stability. Factors that have the same magnitude in the prototype and in the model have a scaling factor of 1.

Example

Consider a straight gravity dam with a triangular cross section such as that shown in Figure 1. The typical nonoverflow monolith is 40 ft wide. The dam is 100 ft high, and the base width is 75 ft. The water depth is 90 ft. The dam has no effective drainage and essentially zero tailwater depth. The customary unit weights will be used in the analysis: 150 pcf for concrete, 62.5 pcf for water. A limit equilibrium analysis will be used to evaluate sliding stability. The model is built at 1:50 scale. See Table 2 for a comparison of parameters for the example.

Discussion

The example was a simple triangular section. The strength of physical modeling is that the technique can be used on sections with complex geometry with geologic features such as bedding planes and shear zones included. In addition, it may be possible to test a model of an entire dam or lock provide a 3-D evaluation of stability. Structures often use shear keys in the foundation

Table 1
Summary of Scaling Factors

Parameter	Scale Factor
Volume	n^3
Weight	n^3
Water force (horizontal)	n^3
Uplift (force)	n^3
Forces (normal, resultant)	n^3
Water pressure	n
Stress (normal, shear)	n
Cohesion (note 1)	n
Strength (notes 1 and 2)	n^3
Moments (note 3)	n^4
Eccentricity (note 4)	1
Factor of safety (notes 1 and 5)	1
Zero compression zone (note 6)	1
Moduli (note 7)	n

Notes:
(1) Cohesion in the model must be $1/n^{th}$ of the cohesion in the prototype for the strength and the factor of safety in the model to equal that of the prototype.

(2) Strength defined by Mohr's expression for shear strength in terms of forces, $T_f - cA + N \tan\Phi$.

(3) Moments used in overturning analysis.

(4) Eccentricity defined as the ratio of the distance between the center of the base and the location of the resultant acting on the section, to the length of the base.

(5) Factor of safety defined as ratio of strength (force) to horizontal force. The factor of safety is dimensionless (force/force).

(6) Zero compression zone (% of base) was not calculated in the example. The entire base was in compression. The scale factor is 1 in those cases where a zero compression zone exists.

(7) The strain in the model is $1/n^{th}$ of the strain in the prototype, unless the moduli are reduced. In soil/structure interaction problems, it is important to scale the moduli to produce realistic kinematics. It is recognized that strain scaling has no effect on the calculations that follow. Nevertheless, strain compatibility may be necessary if the experimental test results are to be compared to finite element analysis.

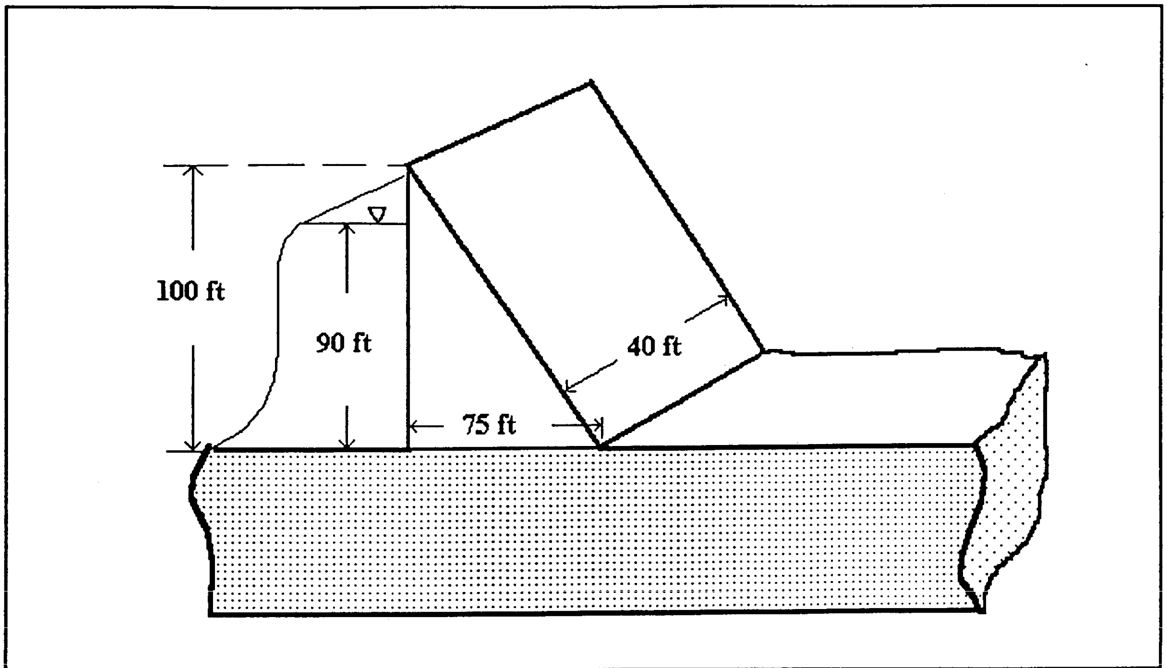

Figure 1. Nonoverflow monolith

Table 2
Comparison of Parameters for Example

Parameter	Prototype	Model
Volume (ft^3)	150,000	1.2
Weight (lb)	22,500,000	180
Water force (horizontal) (lb)	10,125,000	81
Uplift (force) (lb)	8,437,500	67.5
Water pressure (psf)	5,625	112.5
Forces (normal-resultant) (lb)	14,062,500	112.5
Strength (c = 5,000 psf, $\Phi = 40^\circ$	26,799,839	--
Strength (c = 100 psf, $\Phi = 40^\circ$	--	214
Eccentricity	0.12	0.12
Factor of safety	2.65	2.65

and monolith shear keys to transfer stresses from one monolith to another. Structures on rock sometimes are built on a rock bench. None of these features can be reliably accounted for in traditional analyses, but all of these features may be built into a model and tested.

Conclusions

Physical models can incorporate geologic features and complicated geometry. The factor of safety in the model during the test is equivalent to the safety factor in the prototype, as measured by customary limit equilibrium analysis, if the cohesion of model material is reduced in proportion to the scale of the model.