Screenings from the Soil Research Lab

IOWA ENGINEERING EXPERIMENT STATION
IOWA STATE UNIVERSITY of Science and Technology
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IN DEFENSE OF CENTENNIALS

Spring is spilling out a merry cascade, and the Centennial fever is upon us. We say hallelujah! and hats off to Iowa State College, now in her one-hundredth year. A very happy time, and a merry time for visitors. May we suggest you see Veishea, the nationally known student-run fair, May 15-17. Education with plenty of action and color, and one century of change.

Ah, but perhaps the intellect rebels; you specialize in the frailties of human endeavor and see anniversaries as an excuse for nonsense. True, true. But nonsense must have its charm, or would we consent to be civilized? What is life, but a long happy string of nonsense, welded together by Bromo Seltzer? A proper celebration requires remoteness of responsibility--we say Happy Birthday to the son but never to the father. Therefore Happy Birthday to Iowa State College, may she live long and happy and continue to pay our salary. And no nonsense.

GOLDEN ANNIVERSARY

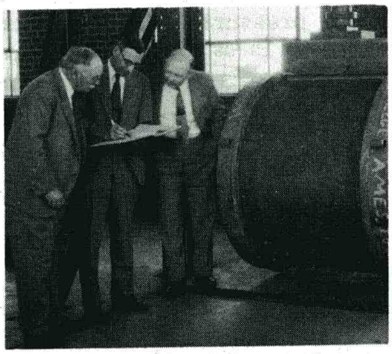
Whoa there, calendar; our day overfloweth with celebrated events. Just four years ago the Iowa Engineering Experiment Station, one of the first two in this country, turned 50, and now we're nearing the fiftieth anniversary of the start of some celebrated research in soil mechanics.

Concrete culvert construction in the Good Old Days. This is a teaching demonstration in 1905. The Iowa Engineering Experiment Station was then one year old.

PIPE DREAMS

In 1909 Professor Anson Marston, then director of the Engineering Experiment Station, undertook to learn the truth about the earth loads on buried pipe.

Use of pipes and conduits is old as civilization, but prior to 1909 the design was based on experience plus frisky amounts of guesswork. Then the uses of pipe changed so fast that guesswork, no matter how frisky, could no longer keep up. Everywhere pipe cracked or broke--particularly the large drainage pipe coming into use at that time. Nothing is quite so useless as a caved-in drainage tile, unless it's to have the replacement tile cave in as well. Many failures involved cracked tile which filled with soil. Research became vital.



A rare photo--from the left are Anson Marston, Dean Emeritus of Engineering and author of the Marston Theory, W. J. Schlick, known for his studies of cast iron pipe; and T. R. Agg, then Dean of Engineering. Photo taken about 1940. All three have since passed on.

Theoretical Approach

Theory has all the beauty and refreshing symmetry of a pretty girl emerging from her bath. A theory perceives a basic truth and avoids witless tangles with impertinent adornments. If one has a car with a rattle he can either develop a theory for locating the rattle, or he can take the car apart, piece by piece, eventually uncovering the rattle. Both methods work, but one is decidedly slower.

The drain tile problem is an excellent, almost classic, example of a theoretical approach. The original theory was proposed and proved, then this led to new theories and applications which are vastly more complex. They would have been impossible without the good groundwork.

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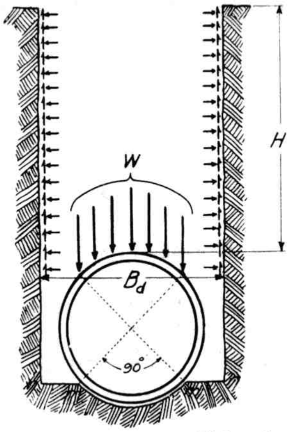
MARSTON'S THEORY

In Ditches

Calculation of the load on pipe in a ditch now looks so simple one wonders why all the fuss. Briefly, the load equals the weight of the backfill minus the frictional support the fill gains from the ditch walls.



What about other factors, such as the shape of the pipe? Relatively unimportant. Skipping the mathematical gymnastics the equation is

$$W_c = C_d w B_d^2$$

where W_c is the load in pounds per linear foot of pipe, C_d is a coefficient, w is the unit weight of backfill in pounds per cubic foot, and B_d is the breadth of the ditch <u>at or a little below the top of the pipe</u>. C_d depends on fill dimensions, the coefficient of friction of the soil, and the ratio between lateral and vertical earth pressures from the backfill. For convenience C_d is usually read from a graph. To impress the natives we can give its equation:

$$C_d = \frac{1 - e^{-2K\mu' \frac{H}{B_d}}}{2K\mu'}$$

where

$$K = \tan^2(45° - \frac{\phi}{2}).$$

Fortunately it's not necessary to read these equations to know what's going on. We merely present them to show that even the simple case is not entirely easy.

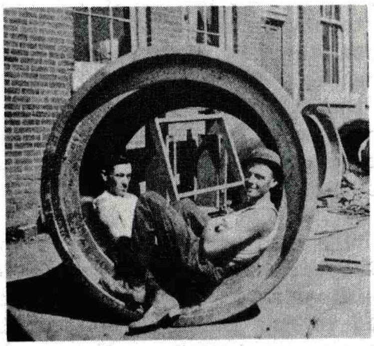
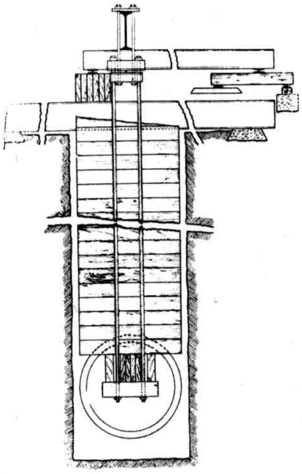


Photo reprinted from Iowa Engineering Experiment Station Bulletin 31, 1913. The caption reads "Forty-Two Inch Vitrified Clay Sewer Pipe, about to be placed in the Testing Machine" Always a joker in the deck.



Test apparatus to measure loads on underground pipe in ditches. Soil is held in by wooden end panels.

Verification

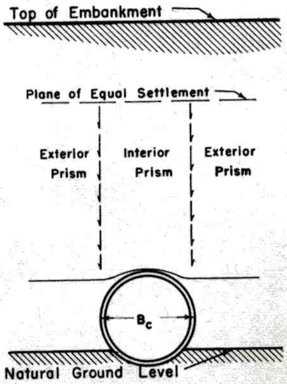
The proof of a theory is in the testing, and needless to say this theory has been pretty well verified or we wouldn't be talking about it.

That could have been the end of the research, but it wasn't. One thing leads to another, and the success with drain tile led to tests on...

CULVERTS

Culvert pipe under highways and railways are not laid in ditches; they are laid on the surface of the ground and then covered by the embankment. They are called "projecting conduits" since they project up into the soil. How does one calculate the loads on a culvert pipe? It takes more theory:

Load experiments were started in 1915 and again in 1919, with some time out for the Great War. The mathematics proved much more tricky than for ditch conduit, and it was not until 1922--seven years after the research began--that Marston announced the solution.



The key was in the conception and mathematical proof of a "plane of equal settlement" at some level in the embankment. A glance at the sketch shows the analogy to the ditch condition. However, frictional forces

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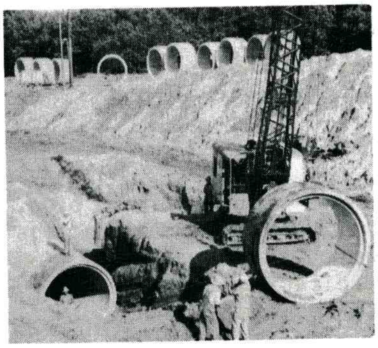


Laying some big ones, 108" (9 feet) in diameter. Cedar Rapids, Iowa; 1949.

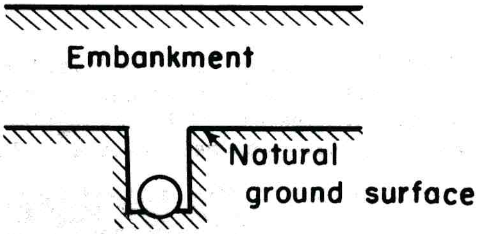
push down on soil over the pipe rather than pushing up to help support the soil. The outer "exterior prism" settles more and drags down on the "interior prism," increasing the load on the pipe. Obviously not a very good deal. The equation may be written the same:

$$W_c = C_c w B_c^2$$

The additional factors of height of the plane of equal settlement and reversal of the friction forces are taken into account through C_c. If the embankment is shallow, the plane of equal settlement may be imaginary, existing above the embankment surface.

Negative Projecting Conduits

The solution for projecting conduits showed the advantage of using a ditch--the load is reduced on the pipe. The next step was to invent the "negative projection" condition, where pipe under an embankment are first laid in a ditch. Soil settles more over the ditch, drag forces are reversed, and the interior prism becomes partially supported. Bravo! for a good idea; and experiments show it works. The same load equation is used, but C depends on additional factors including the depth of the ditch.

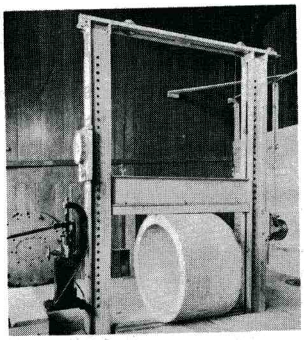


Time

Loads on pipe are partly caused by invisible friction forces in the soil--but are these forces permanent? To answer this, test culverts loaded in 1927 were periodically checked for about 20 years. Result? Indeed the loading is permanent, reaching a maximum during the spring of each year.

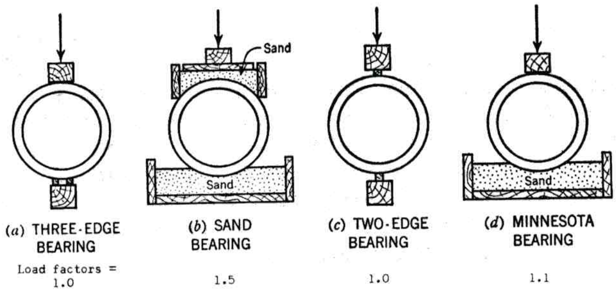
STRENGTH TESTS

'Way back among the whispers of the past somebody invented the testing machine, and engineers have been breaking things ever since. Ladies, if your small boy likes to see things go smash consider it a good sign; he may grow up to be an engineer.



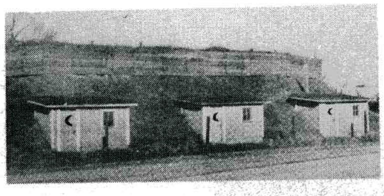
Three-edge bearing test of a large concrete pipe. Date, 1929.

As any small boy will tell you, testing is not without its purpose. He tests in order to see if and how things break. For example, what good does it do to calculate the loads on a pipe if one doesn't know the strength of the pipe? A woman buying a girdle has to know at least two specifications with regard to size--hers, and its; then she subtracts a little. An engineer would call this a factor of safety, with due regard that it is in the wrong direction.



Laboratory testing of circular pipe. Strengths of other shapes such as box culverts may be calculated from engineering mechanics.

Typical test bearing setups for the pipe and tile tests are shown above. For convenience the three-edge bearing test is most often used. Values obtained in other tests are divided by a load factor to obtain the equivalent three-edge bearing value. Note that the distributed loading conditions give better strength.



Embankment and scale houses for measuring loads on culvert pipe.

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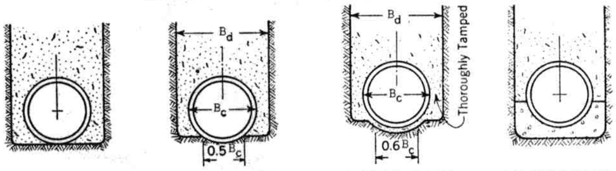
BEDDING AND LOAD FACTORS

A soft bed improves sleep and prevents a broken back, provided there is not undue sag in the region of greatest loading.

Calculation has given the loads on pipe after installation, and a testing machine gives pipe strengths--the next step is to try to link the two. The main difference between testing machine strengths and those effective in the field lay in the bedding under the pipe, or care with which the bed was prepared to spread the load.



(*a*) NOT PERMISSIBLE (*b*) ORDINARY (*c*) FIRST CLASS (*d*) CONCRETE CRADLE

Load factors = 1.5 1.9 2.25 to 3.4

Pipe bedding in ditches was classified by Professor W. J. Schlick of the Iowa Engineering Experiment Station as Impermissible, Ordinary, First Class, and Concrete Cradle. Extensive testing gave load factors as shown; the better the bedding, the greater the permissible load.

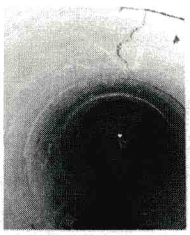
Bedding of Projecting Conduits

Load factors of culvert pipe in embankments are quite a bit more tricky than for pipe in ditches because the compacted embankment material lends lateral support to the pipe. Again development of a theory provided a much needed shortcut. In 1933 Professor M. G. Spangler of the Iowa Engineering Experiment Station published his mathematical analysis and supporting data, and another mystery expired.

Load factors on projecting conduits are calculated from

$$L_f = \frac{1.431}{N - xq}$$

where N depends on bedding, x depends on the amount of projection, and q is the ratio of lateral pressure to vertical load. Calculation is improved by use of tables and graphs. For the first-class bedding the L_f is commonly 2.0 to 2.3, meaning the pipe in effect becomes over twice as strong.



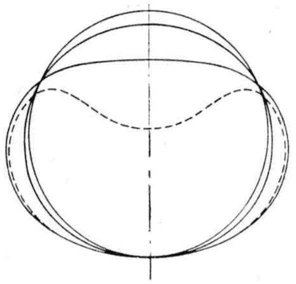
Failures in reinforced concrete culvert pipe. Cracks and spalled concrete allow the steel reinforcement to corrode.

END OF THE ROAD? NEW ROUTES TO FOLLOW

Thus ends the story of loads on rigid pipe, may a cracked tile or culvert be as rare as hogs elbows. But is it ended? Actually research then took three different directions and continued up until about 1949. For example...

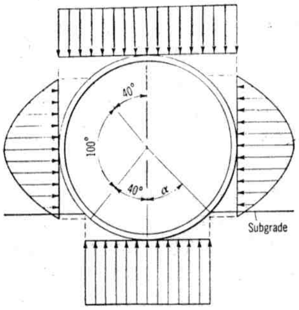
Flexible Pipes

Many culverts are constructed with corrugated sheet metal pipe having comparatively little inherent rigidity. Pressure on the top causes sides to bulge, but collapse is opposed by resulting earth pressure on the side walls.

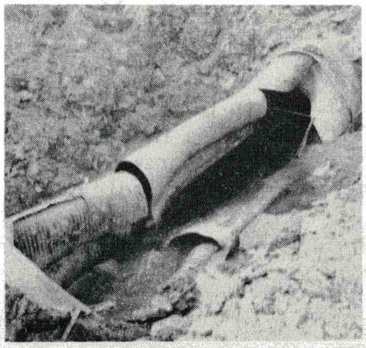


Stages in deformation of a flexible conduit.

Spangler's work extending from 1927 to 1941 showed that circular flexible pipe under load behave in accordance with mathematical theory for elastic rings, a bold trick if you can do it. Briefly, the vertical load is distributed uniformly over the breadth of the pipe, and the support from below is exerted evenly over the width of the bedding. The side pressures caused by deformation then have a parabolic distribution.



Most interesting is the question how do flexible pipe fail? They can't crack, so the top folds in. The amount of deflection, not the amount of stress, becomes critical. Deflection



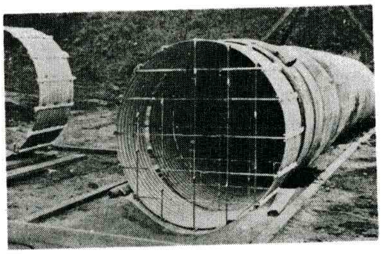
Failure of a flexible corrugated metal culvert pipe. Note how the top has folded in from the weight of the soil.

is usually limited to 5 percent of the initial pipe diameter. Spangler's formula is

$$\Delta x = D_1 \frac{KW_c r^3}{EI + 0.061(er)r^3}$$

where Δx is the horizontal deflection in inches (about equal to vertical deflection), D_1 is a deflection lag factor (normally 1.25 to 1.50), and other factors take into account the effects of bedding, vertical load, and pipe radius and stiffness.

One of the most important factors is "e," which is the "modulus of passive resistance," and represents the rapidity with which lateral earth pressures build up as the pipe squashes out. Anything that increases e improves strength. Therefore fill material alongside the pipe should be good stuff well compacted.

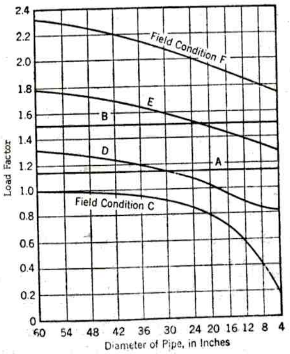


Stainless steel "friction ribbons" measure soil pressures against the outside of corrugated flexible pipe.

Pipe with Internal Pressure

Simultaneously with the flexible conduit research W. J. Schlick in 1926-1940 checked up on the added effects of earth load and internal pressures on cast-iron pipe such as used for water, gas or oil.

The first step was to recognize that field practice required a different evaluation of bedding conditions. Condition F means a shaped-bottom trench with the backfill firmly tamped in and around the pipe. Condition C has the pipe set on blocks with no tamping of the backfill. Obviously it makes a difference.



Schlick found that the relationship between internal pressure and three-edge bearing strength at the time of failure is

$$t = T\left[1 - \left(\frac{s}{S}\right)^2\right]$$

where T is the bursting strength of the pipe, S is the three-edged bearing strength without internal pressure, and s is the three-edged bearing strength when the pipe has infernal pressure. As pressure t increases, strength s decreases.

Prof. M. G. (Ib) Spangler, author of Soil Engineering and the world's foremost "Mr. Underground Conduits."

Wheel Loads

So much for soil loads; properly designed, a pipe will now be adequate unless you want to drive over it. Undoubtedly loads on pipes are increased by the weight of cars, trucks, trains, planes, and small burrowing animals. But how much is the load, and how would you design for it? More research, please.

Nowadays when you say "Boussinesq" to a soil engineer he hears music of a most enchanting and elegant variety. He is likely to swoon. But thirty years ago he wouldn't have known what you were talking about.

One of the first men to suggest application of the Boussinesq equations to soils was Prof. John H. "Pop" Griffith of the Iowa Engineering Experiment Station. Griffith was a deep, bold and undisciplined thinker. Many of his theories even after 20 years are not completely understood; others are understood too well. It's not surprising that at least one carries real dynamite. Persons fascinated by the unusual should check Iowa Engineering Experiment Station Bulletin 117, 1934.

Extensive experiments in the 1920's showed that Griffith's suggestion carried weight, literally, and wheel loads are transmitted substantially in accord with the Boussinesq solution. Results were published in 1926. The upshot is that the effect of traffic loads rapidly decreases as the height of the fill increases. In other words the pipe is protected by the fill.

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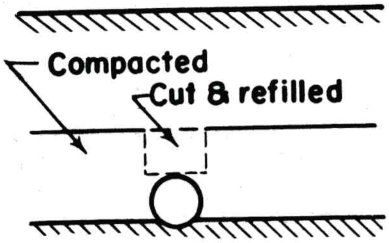
ESSAY ON THE "IMPERFECT DITCH"

"Imperfect ditch" doesn't exactly mean a poor ditch, as the name might imply; it is a method first suggested by Marston in 1919 to reduce the loads on culverts under high fills. The theory of loads was worked out by Spangler and experimentally proved by Schlick prior to 1952.

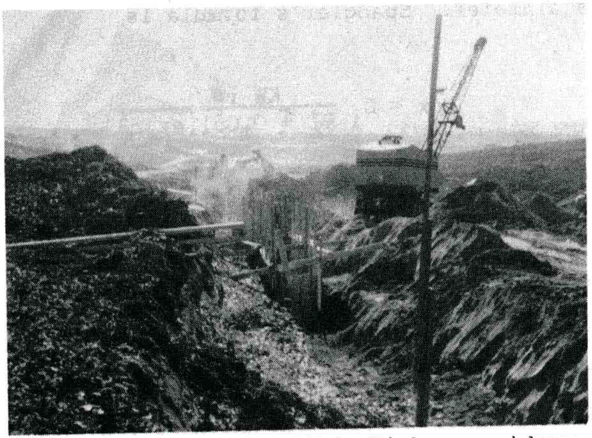
In the Imperfect Ditch Method part of the fill is placed and compacted, then a ditch is dug in the compacted fill above the pipe. The ditch is then backfilled with loose material.



The Imperfect Ditch operates by increasing settlement of the "interior prism" of soil above the pipe so that drag helps to hold the soil up. The method is somewhat analogous to the use of negative projection conduits, described on p. 3.

An interesting application of the Imperfect Ditch Method was in 1955 in Atlanta, Georgia. A reinforced concrete pipe sewer built in 1937 was in bad odor with the Southern Railway because they wanted to increase the height of the fill from a former maximum of 35 feet to a new level of 95.5 feet. Calculations showed the sewer couldn't take it unless somebody got tricky with the fill.

First a ditch was dug from material already on top of the sewer. The backfill was loose soil, and to make sure it remained loose it included three layers of leaves. The leaves may rot out, but who cares? The interior prism is supported by shear forces, which tests prove can last for many years. The method worked, and the city of Atlanta saved about $130,000 from the price of a new sewer.


Backfilling the Imperfect Ditch with leaves and loose soil preparatory to increasing the height of the fill.

THE LAST WORD, OR IS IT THE LAST?

Where basic research has been sound and true, applications can go on and on.

Most recently the Marston and Boussinesq Theories have been applied to the problem of high pressure gas and oil pipeline crossings under railways and highways, something unheard of 40 years ago. All the more credit to the basic research. What's next? Who knows?

ACKNOWLEDGEMENTS, REFERENCES SIGHTED

These 40 odd years of research (pardon us for being odd) were sponsored by the Iowa Engineering Experiment Station, the Bureau of Public Roads, and the National Bureau of Standards. Results have taken well over a dozen bulletins and many technical papers. Obviously in this review many things have been skipped over, or just plain skipped. A more detailed summary of the Iowa work is, "Underground Conduits--an Appraisal of Modern Research," by M. G. Spangler, ASCE Transactions, 113: 316-374, 1948.

Two excellant design manuals for flexible and rigid conduit are Handbook of Drainage and Construction Products, published by Armco Drainage and Metal Products, Inc., Middletown, Ohio; Concrete Pipe Handbook, published by the American Concrete Pipe Association, Chicago, Illinois. Design of cast iron pressure pipe is described in Manual for the Computation of Strength and Thickness of Cast Iron Pipe, published by the American Water Works Association, Inc., New York.

IN THE NEXT ISSUE: Soil-cement for low-cost roads.

RLH

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