223

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Bulletin 223

Embedded Flexible Metal Pipe Culverts

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Corrosion and Deformation

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Contents

Corrosion of Corrugated Metal Culverts in California

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The history of corrugated metal culvert pipes under California highways has been punctuated with predictions of service life varying from 10 to 100 years. These predictions of the anticipated service life of such pipe, as employed in highway drainage structures, were not made without some foundation of field experience. However, the results of inspecting approximately 7,000 metal culverts in a portion of northern California indicated that the previously estimated service life of 10 or 100 years would depend on the fundamental factors of abrasion and corrosion as these influences develop in the geographic location in which the experience was accumulated.

Altogether this survey indicated that specific types of rust accompanied accelerated corrosion and that the only reliable method of evaluating service life by comparative culvert inspection was to estimate the actual loss of culvert metal.

The thickness or the type of rust formed on the culvert cannot be used as a criterion of severe corrosion because the appearance of the corrosion products varies in relation to the geographic location. In specific locations, however, the type or thickness of the rust can be employed to indicate something of the general magnitude of corrosion in culverts.

In practice, rapid field inspection can be implemented by striking the culvert with a geologist's pick and then estimating the remaining metal thickness from the penetration or rebound of the pick.

In coastal, and later, other geographic locations, it was observed that accelerated corrosion was apparently linked to the presence of anaerobic bacteria in the watershed. This factor has now been correlated by the data accumulated through the classification of the watershed soil types to the presence of sulfate-reducing or related bacteria, which release hydrogen sulfide to the soil, or to the drainage waters from such soils.

The research program covering the causes the mechanism or corrosion of metal culverts is continuing, as it is obviously prudent to develop laboratory or field tests to predict whether or not a specific location is favorable to an economical life for metal culvert installation.

●IN THE northwest district of the California State Highway System (District 1) there are more than 7,000 corrugated metal culverts utilized as highway drainage structures. Some of these culverts were placed more than 40 years ago. A large percentage of these have been in use in excess of 20 years. As a result of this lengthy installation period, a reasonable percentage of culverts is showing signs of distress due to corrosion of the metal.

By 1950 the number of metal culverts reported to be in critical condition appeared to be increasing beyond that considered to be normal. This was resulting in unanticipated expenditures. For instance, when one section of highway was selected to be widened, it was found necessary to spend an additional $30,000 to replace a failed metal culvert under the old section before the pipe could be extended under the new. As a result, an investigation of the condition of the metal culverts in this one highway district was undertaken in 1953 and completed in 1954 so as to prepare a systematic replacement program and also to locate those areas where accelerated corrosion was likely to occur.

Generally, where corrosion was evident, it was found that the culverts were attacked primarily in the invert. It also was apparent that the chemicals or soils in the watershed over which the runoff water flows are a predominant factor affecting the corrosion rate of the metal pipes. Because of the apparent influence of the watershed soils on the corrosion of the metal culverts, the work of Starkey and Wight (1), and Kulman (2), on the corrosive effect of anaerobic bacteria was of special significance in this investigation.

While the scope of this investigation was limited to physical and visual tests, there is no doubt that the apparent presence of the sulfate reducing anaerobic bacteria, as indicated by the presence of hydrogen sulfide gas, is an important factor in the rate of culvert corrosion in this area.

In searching through the literature on the corrosion of metals (1) through (8), and the corrosion of metal culverts (9) through (13), it was apparent that the corrosion of metal culverts is a relatively unexplored field.

Because of the great variety of environments and the types and locations of attack which exist in the culverts in California, the inspection methods used by other investigators (9) through (13) were not sufficiently flexible to provide an objective set of data. For this reason a destructive type of test was devised to judge the amount of culvert metal lost by corrosion.

SURVEY METHODS EMPLOYED IN THIS STUDY OF CULVERT PIPES

In order to expedite this survey, which required work in the cramped and poorly accessible spaces peculiar to culvert studies, it was necessary to devise a quick, even though approximate, method of evaluating metal loss.

In estimating the relative metal loss of the culverts, the penetration or rebound of a geologist's pick striking the culvert was transposed in terms of percentage of original metal lost. The penetration or rebound from the blow of the pick was compared and standardized by comparing it to culvert metal of known thickness. After a short training period it was found that the survey personnel could obtain remarkable accuracy in determining the thickness of remaining culvert metal.

The ease and flexibility of this inspection method is clearly indicated by the time required for inspection and metal loss determinations of approximately 7,000 culverts. This survey was completed by a crew which averaged three men in 7 months of inspection time. It was not unusual to inspect 10 culverts per hour, even in mountainous terrain.

The inspection of culverts by striking the invert with a geologist's pick proved invaluable in determining the condition of culverts. For instance, culverts were observed with the invert rusted but with no visual perforations to indicate that the pipe was in other than relatively good condition. Yet, when the invert was struck with the geologist's pick, it was found that the invert of the pipe consisted of rust alone.

In some cases, expecially in the same geographic locality, the appearance of a certain type or thickness of rust would indicate to some measure the condition of the pipe. However, the judgment of the condition of a culvert by the singular observation of rust or the lack of perforation would be misleading unless the inspector was an expert in correlating metal loss to the numerous types and thicknesses of rust.

It might also be mentioned that in the arid desert areas, culverts were observed in which the spelter coating was apparently intact on the inside of the pipe, and the pipe would be judged to be in practically new condition. However, after testing the pipe with the geologist's pick, it would be found that the culvert had experienced considerable corrosion from the soil side of the pipe.

Some of the typical variations in the appearance of corroded culverts are shown by Figures 8, 9, and 10. Figure 8 shows the rusted appearance of a culvert invert as a result of a corrosive flow. Figure 9 depicts the appearance of the invert of a culvert located in an alkali soil area. The rainfall in this area containing alkali soil is approximately 3 in. per year. The effect of the infrequent flow was to merely stain the culvert invert, but there are random perforations in the pipe wall as a result of the corrosive backfill soil.

Figure 10 shows the corroded surface of a pipe contacting a corrosive backfill soil.

It is obvious that if the culvert depicted in Figures 9 and 10 was visually inspected immediately prior to the time it was perforated by corrosion, it would have been judged to be in excellent condition, wherein an evaluation of the culvert condition with a geologist's pick would have indicated a pipe condition of considerable metal loss.

Other factors tabulated in the survey included height of fill over the culvert, asphalt coating conditions, rust type, location and extent of metal deterioration, presence and origin of water, etc. A detailed explanation of the physical factors observed and a sample culvert inspection record sheet are included as Figures 1 through 6.

WATERSHED SOILS AND ACCELERATED CORROSION

In California there are areas where corrugated metal pipes have an economically long service life, and there are adjacent locations where the service life is short. An example of this variable service life of metal culverts is shown by Figure 7. This exhibit compares the service life of culverts installed in two distant sections of road, each approximately 12 miles in length. The corrosion rate of culverts in one of these areas is relatively rapid and variable, whereas the other is slow and consistent.

In judging the physical differences encountered in coastal areas where the culverts corrode at a relatively rapid rate and the inland areas where the culverts corrode at a slow rate, it was found that approximately 58 percent of the culverts in the coastal area carried year-round water flow as compared with only 2 percent in the inland location. This statistic within itself indicates that the presence of ground or surface water flow is a direct factor contributing to the accelerated corrosion of the culvert invert.

Although there were many cases where the presence of a continuous flow did not accompany an excessive corrosion rate, its presence does indicate a potentially corrosive location where additional protection of the galvanized culvert metal should be considered in the economic design of the structure.

The investigation of Starkey and Wight indicated that a soil which is non-aerated and which contains organic matter would support anaerobic bacteria. Also, their studies confirmed the fact that the corrosion rate of metal would be accelerated by anaerobic bacteria. An extreme example of this soil type would be a swamp land. When this soil is disturbed, an odor of hydrogen sulfide may be perceived. The anaerobic bacteria form hydrogen sulfide, and hydrogen sulfide may be oxidized to form sulfurous and sulfuric acids, which are highly corrosive.

Since such bacteria are associated with organic reducing soils, a criterion was established in this survey that any soil which released perceptible quantities of hydrogen sulfide gas, when physically disturbed, was an organic reducing soil. The criteria used in this study to classify the watershed soils are described in Figure 3.

After observing 7,000 culverts, it was apparent that rainfall, abrasion, and invert silting would influence the rate of corrosion. However, it was also apparent that if a sufficient number of culverts were analyzed in a relatively large geographic area, the effect of the environment would evolve into a statistical mean and the influence of the watershed soils could then be determined.

Therefore, the service life of each culvert was plotted on a linear profile of the highway, and the geographic areas were defined by the corrosion rate of the culverts. A typical example of the type of plot used to define the geographic service life areas is shown in Figure 7.

After the service life of the culverts in each geographic area was determined, the distribution of watershed soil types was tabulated to ascertain the influence of soils on culvert corrosion.

When the soil types were classified and tabulated, it was found that 35 percent of the watersheds in the more corrosive geographic areas contained organic reducing soils, whereas only 1 percent of the watersheds in the least corrosive areas involved soils of this type.

The predominate soil type found in the least corrosive geographic area was "inorganic oxidizing." Such inorganic oxidizing soils are defined as a soil containing less than 50 percent vegetation cover with the vegetation disintegrated by oxidation or by the process of drying.

Although the greatest number of organic reducing type soils were found in the coastal areas, it should be brought out that like soils have been observed throughout California. Observations indicated that any watershed soil, varying from clays to sands, could become an organic reducing type if the soil was continually saturated and sufficient vegetation or other organic matter was available to result in reducing conditions. Moisture saturation of the soil may occur when water is in a ponded condition or when the aeration of the heavy soil such as a clay is prevented by heavy vegetation or by the prolonged presence of moisture in the form of fog, rain, or seepage.

The physical condition of a culvert is determined from the reaction or penetration of a prospector's pick to the metal surface and is described in % of original metal thickness lost.

The inspection report is to be filled out in such a manner that an engineer in the office can visualize the physical condition of a culvert in the field.

The following terminology is to be used on the inspection report to describe the varying culvert conditions:

INLET SECTION

Column	Abbreviation	Definition and Procedure
Type	Gal.	Galvanized C.M.P.
	A.D.	Asphalt dip C.M.P.
	A.B.	Asbestos bonded C.M.P.
	A.P.I.	Asphalt paved invert
	C.P.I.	Concrete paved invert
	R.C.P.	Reinforced concrete pipe
	P.C.P.	Plain concrete pipe
	R.C.B.	Reinforced concrete box
	P.C.B.	Plain concrete box
Installed 19___		The year the culvert was installed shall be inserted in this column.
	M.	Date of culvert installation not checked on plans. Installation date obtained from Maintenance foreman or other verbal source. Example: 25M - culvert installed in 1925, date obtained from maintenance forces.
Cond. Length		Designates the length in feet of culvert inspected visually or by test.
	A	Air
	W	Water
	V	Visual
		Example: A3 - the inlet or outlet section of the culvert projects 3' beyond the fill. The outside bottom section normally in contact with soil is in contact with air.
Silt Depth		Depth of silt designated in inches above the culvert invert.
Upstream ridge		The upstream face of a corrugation.

Figure 1. Culvert inspection instructions.

As will be noted in Table 1, the organic reducing and the organic oxidizing soils predominate in the more corrosive areas while the inorganic oxidizing soils predominate in the lease corrosive area. Therefore, as indicated by this study, the presence of an organic reducing watershed would indicate a potentially corrosive location and an inorganic oxidizing watershed would indicate a non-corrosive site.

Column	Abbreviation	Definition and Procedure
	G	General
	P	Pit
	0 thru 10(x)	Describes metal loss in terms of % of original metal thickness. 1 = 10%, 2 = 20%, X = 100%
	0 thru 10(x)	Describes total area in %. 1 = 10%, 2 = 20%, X = 100%
		Example: 6P9 - 60% of the corrosion area has pits to a depth of 90% of the original metal thickness.
Splash	See upstream ridge	Area inside culvert where normal flow of water fluctuates or splashes most often.
Air		Designates corrosion area not in contact with soil or flowing water.
	O	Outside
	I	Inside
	0 thru 10(x)	1 = 10%, 2 = 20%, X = 100%
		Example: O1 designates that the outside section of culvert (section most likely to get direct sunlight) has lost 10% of its original metal thickness.
Soil		Designates the culvert section in contact with earth backfill.
Abrasion	0 thru 10(x)	1 = 10%, 5 = 50%, X = 100% A numeral in this column is the inspector's opinion of how much of the culvert metal loss is caused by abrasion.
Rust Type	Flake	Hard, adherent stratified rust flakes. Usually a black or a dark colored layer of rust adjacent to the metal surface.
	Fine powder	Relatively smooth to the touch, about the consistency of cement. Usually found with soil contact. Generally light in color.
	Coarse powder	Granular, relatively adherent. Usually found in atmospheric corrosion. Color varies from light to dark reddish brown.
	Tubercle	Generally are hard nodules of rust. Usually has a dark or black colored rust layer adjacent to metal surface. Usually found in areas subject to runoff water or sea water attack. Sometimes gelatinous in appearance. Indicates pitting of metal.

Figure 2. Culvert inspection instructions.

It may be that the organic reducing soils are more significant than indicated as there appears to be a definite probability that some of the soils classified as organic oxidizing may revert to organic reducing condition when the environmental conditions are favorable. For instance, during the winter rainfall in a certain watershed reducing conditions may prevail, while in the relatively dry summer, oxidizing conditions may predominate

Column	Abbreviation	Definition or example
	W	Water
	H	Splash
	S	Soil
	A	Air
	O	Outside
	I	Inside
Asphalt Coating		Location of condition of asphalt coating is the same as rust type location.
Fill Shoulder		Height in feet from the crown of the culvert to the highway shoulder.
Metal Gage		This is the standard sheet metal thickness of the culvert steel.
Waterway		The adequacy of the waterway is determined by visual observation and/or statements by maintenance forces. If the roadway floods because the culvert is inadequate, designate the reason.
	W	Waterway
	S	Silt
	D	Debris
	P	Profile of road
EARTH TYPE		
Organic		Watershed has more than 50% of land area covered by vegetation.
Inorganic		Watershed has less than 50% of land area covered by vegetation.
Reducing		Generally the soil is dark or mottled gray and black in color. Very often an odor similar to decomposing sewerage (H_2S) is perceived when moist soil is exposed a few inches below the surface.
Oxidizing		Land is well drained in an agricultural sense. Generally a light colored soil.
		Examples:
		1. Inorganic Oxidizing: May be sand dunes or rocky watersheds with little topsoil or vegetation.
		2. Organic Reducing: May be marshland or watersheds similar to those found on the coast. Odor of H_2S perceived.

Figure 3. Culvert inspection instructions.

TABLE 1

PERCENT OF TOTAL CULVERTS IN EACH SOIL CLASSIFICATION AREA IN ACCORDANCE TO SERVICE LIFE

Watershed Soil Type	Geographic Area Service Life		
	20 years or less (%)	20 to 30 years (%)	30 years or greater (%)
Organic reducing	33	5	1
Organic oxidizing	62	54	11
Inorganic oxidizing	5	41	88
Number of culverts	1820	2590	2590

in the same watershed. Such variable conditions are possible as evidenced by the work of Starkey and Wight. All soils were classified during the summer months of the year, because high flow during the winter made inspections impossible.

An organic reducing soil as such may or may not indicate whether the watershed contains sulfate-reducing bacteria. These bacteria are generally recognized as Sporovibrio desulfuricans. In order to actually determine the presence of these bacteria, pathological studies are required. However, this was beyond the scope of this investigation.

DISCUSSION

As previously discussed, corrosion of metal culverts on the coastal sections of highway was rapid when compared to the inland sections of highway. As the corrosion rate of metal culverts in the coastal sections of highway is more marked than in the inland sections, the normal reaction of an investigator might be to judge the corrosion rate to be due to the effect of salt air. Unfortunately, this investigation did not formally evaluate the effect of salt air on the corrosion of metal culverts. However, chloride

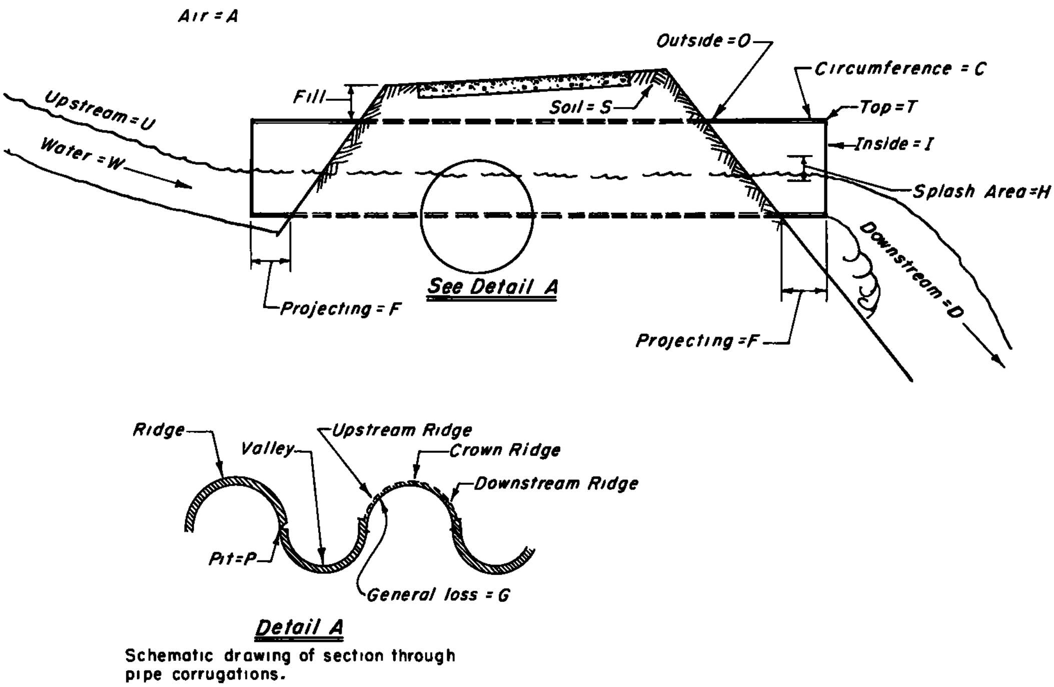

Figure 4. Culvert inspection terminology.

tests were performed on a few random water samples taken within a mile of the coast. The analysis indicated a range of 20 to 100 ppm chlorides which corrosion-wise is not considered significant. Also, many observations confirmed the lack of corrosion on the projecting ends of coastal culverts, which were exposed for 20 years to a direct sea exposure. The lack of corrosion on the projecting ends of the culvert indicates that the salt air in itself plays a minor role in the corrosion of highway culverts. Evidence of invert corrosion indicates that the corrosion of a culvert in this coastal location is related primarily to the presence of moisture in the form of rain, fog, and ground water flow, and their resultant promotion of corrosive organic reducing watersheds.

Comparable rates of corrosion and similar corrosion products have been observed in culverts draining organic reducing watersheds in inland and coastal areas, which again indicates that salt air per se plays a minor role in the corrosion rate of culverts.

As will be noted in Figure 7, the corrosion rate of a number of culverts can be plotted for a highway section or a geographic area. A plot of this type can be utilized to designate the average or the economic service life of metal culverts to govern the selection of coatings or pipe materials for future installations in a designated area.

In the highway district in which this survey was performed, a corrosion area map was constructed which broadly defined the geographical areas in which a significant percentage of culverts failed in the following intervals of time: less than 20 years, 20 to 30 years, and greater than 30 years. This corrosion area map is in constant use by the Design and Maintenance departments and is used for the economic selection of coatings or pipe materials.

Since the causes of corrosion of metals were considered to be a complex phenomenon, a study was made of the literature of the factors which could affect the corrosion rate of culverts. Following this discussion is a resumé of the theory of corrosion and some of the pertinent factors which may influence the corrosion rate of culverts.

As there are factors other than flow and anaerobic bacteria which influence the corrosion rate of metal culverts, laboratory and field studies are in progress to develop a testing method to identify and predict a corrosive area.

Mechanism of Corrosion

There are many factors that affect the rate of corrosion of iron or steel in water. The corrosion of ferrous metal in substantially pure water and air can be chemically expressed as $Fe+2H^{+} \gtrless Fe^{++}+2H$. It is common knowledge that two different metals can set up a galvanic corrosion cell. For example, when zinc and copper are immersed in an electrolyte and electrically connected they will become anode and cathode, respectively.

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Existing Culvert																													
			Inlet Section									Center Section									Outlet Section								
							Metal Loss									Metal Loss									Metal Loss				
							Water									Water									Water				
Mile	Station	Size & Length	Type	Installed 19__	Cond. Length	Silt Depth	UpStrm Ridge	Crown Ridge	DnStrm Ridge	Valley	Splash	Type	Installed 19__	Cond. Length	Silt Depth	UpStrm Ridge	Crown Ridge	DnStrm Ridge	Valley	Splash	Type	Installed 19__	Cond. Length	Silt Depth	UpStrm Ridge	Crown Ridge	DnStrm Ridge	Valley	Splash
	799+22	15" x 70'	Gal	25	8	0	69	6x	69	69	-	Gal	25	W48	0	69	6x	69	69	-	18" ADPT	35	14	0	65	65	65	65	-
	802+93	18" x 60'	Gal	25	6	0	68	67	66	66	-	Gal	25	W43	0	68	67	66	66	-	ADXT	35	1	4"	65	65	65	65	-
							3Px	3Px	6Px	4Px	-					3Px	3Px	6Px	4Px	-									
	803+00	12" x 40'	Gal	25	8	0	66	66	67	66	-	Gal	25	W25	0	66	66	67	66	-	Gal	25	2	6"	64	64	64	64	67
							3Px	3Px	6Px	4Px	-					3Px	3Px	6Px	4Px	-					3Px	3Px	6Px	4Px	-
	921+85	18" x 70'	Gal	25	13	0	67	67	67	67	-																		
							5Px	5Px	5Px	5Px	-																		
			Gal	25	3-6	0	65	66	64	64	-	Gal	25	VU (?)	0	65	65	64	64	-	Gal	25	W3	0	68	68	67	69	-
							6Px	5Px	3Px	4Px	-					6Px	5Px	3Px	4Px	-					6Px	5Px	3Px	4Px	-
	922+50	24" x 60'	ADAPT	35	4	0	60	60	60	60	-	ADAPT	35	W52	0	60	60	60	60	-	ADAPT	35	4	0	60	60	60	60	-
	922+75	30" x 50'	Gal CP	26	10	0	6x	6x	6x	6x	6x	RCB	15	30	0						ADAPT	35	10	0	60	60	60	60	-

Figure 5. Sample culvert inspection record.

When these two metals are electrically connected through a galvanometer, a current will be measured, and the zinc will disintegrate. In other words, a battery is formed. It is also true that differences in the electrolyte, such as chemical concentration or differential aeration, will cause anodic and cathodic areas to be set up on a single piece of metal.

By partly immersing specimens of plain carbon steel and also iron in water, and using three independent methods of measurements, Evans and Hoar (7), measured the quantity of electric current flowing between anodic and cathodic areas, and obtained a direct correlation between the current flowing and the weight of metal dissolved. Brown and Mears (5), also Evans and Thornhill (8), obtained the same correlation between current quantity and weight of metal dissolved.

Similarly, the formation of anodic and cathodic areas on the same piece of metal are caused by non-uniformities which exist in all metals, or by non-homogeneous electrolytes.

As summarized by Speller (4), "It may now be regarded as established in substantially all cases of corrosion in the presence of water that the driving force of the corrosion reaction between metal and environment is electrochemical. The magnitude of this electrochemical potential, which varies with the environment and the metal, determines the tendency of the reaction to proceed, whereas the rate of corrosion is determined mainly by the resistance to the continued progress of the reaction set up by certain of the corrosion by-products."

Pertinent Factors Influencing the Rate of Corrosion

During the course of the culvert investigation a number of observations were made concerning factors affecting the rate of corrosion. Those factors considered to be of special significance were recorded. They were: evidence of extreme water hardness, which was indicated by a calcareous deposit in the culvert invert; rust formation, which was recorded as to its particular type, that is, tubercle, flake, powder, etc.; and the evidence of hydrogen sulfide in the watershed soil.

The apparent influence of these significant factors on the accelerated corrosion of metal culverts is discussed as follows:

Influence of Water Hardness. Water not saturated with calcium carbonate is likely to corrode a metal pipe, and water saturated with calcium carbonate is, in general, relatively harmless (6).

The water issuing from a chalk or limestone formation will usually, although not invariably, be in equilibrium with calcium carbonate, that is, will be non-aggressive.

Existing Culvert																								Previous Culvert		
	Metal Loss		Abrasion		Ground Water		Rust Type Location				Asphalt Coating				Fill Shldr			Earth Type				Water Way				
Mile Station	Air	Soil	Yes	No	Yes	No	Flake	Fine Pwdr	Coarse Pwdr	Tubercle	Excellent	Cracking	Chipping	Deteriorated	Inlet	Outlet	Metal Gauge	Organic	Inorganic	Oxidizing	Reducing	Adequate	Inadequate	Installed 19__	Type	REMARKS (Predominant cause of metal loss, etc)
799+32	9'/20	2	2			✓	W	S	OA						8	12	16	✓		✓		✓				Air/Soil rated for galv.
799+32	60	1	2				W	S			TA		OA	SW			16									" / " " " AD-x
802+93	9'/20	2	2			✓	W	S	OA	W					6	15	16	✓		✓		✓				" / " " " galv.
802+93	60	1	2				W	S		W		TA	OA	SW			16									
803+00	9'/20	2		✓		✓	WH	S	OA	W					1	3	16	✓		✓			D			
921+85	9'/20	2		✓		✓	WS	S	OA	W					10	11	16	✓		✓		✓				
922+60	60	1		✓	✓						W	TA	OA	S	15	17	14	✓		✓		✓				
922+75	9'/20	2	S		✓		H	S	OA						20	20	12	✓		✓			W			Air/Soil rated for CPDC
922+75	60	1						S			W	TA	OA	S			12									" / " " " APD-x

Figure 6. Sample culvert inspection record.

However, with very soft water, particularly rain water and some mineral spring water, the attack on a metal pipe is likely to continue indefinitely.

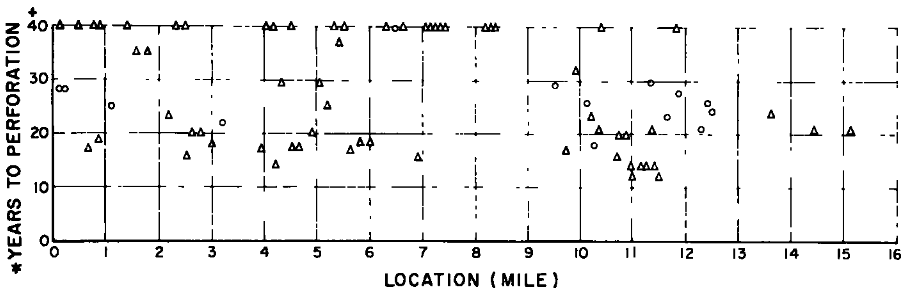
In areas of heavy rainfall, with a quick runoff over saturated ground containing calcium the likelihood of the water becoming saturated with calcium is small. However, if the rate of runoff is slow enough, the water will become saturated with calcium and tend to deposit a calcareous layer in the culvert. Conversely, if the runoff is rapid, any removal of a calcareous deposit in the culvert will depend on the relative frequency of water not saturated with calcium.

The majority of waters used for public supply purposes normally contain a considerable amount of calcium carbonate, which is kept in solution as calcium bi-carbonate through the presence of carbon dioxide. If the excess of carbon dioxide present is just sufficient to keep the calcium carbonate in solution, any incipient corrosion will produce a rise in the pH value at the cathodic regions and will consequently lead to the precipitation of calcium carbonate. This will divert the cathodic reaction elsewhere, so that after a time the whole interior surface of the pipe will have become covered with a layer of calcium carbonate.

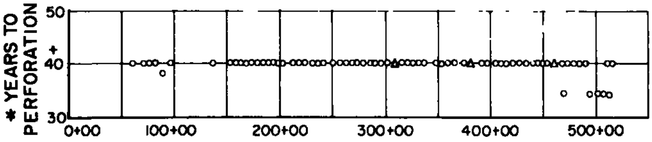
In the presence of sufficient oxygen, this layer of calcium carbonate will interact with iron salts, forming under the calcium carbonate surface a clinging form of ferric oxide rust. For many waters, this layer will be more protective when oxygen is present in large quantities, because the rust will then be formed very close to the metal.

<u>Influence of Rust.</u> In natural waters the precipitated rust usually carries down some compounds containing lime, magnesia, and silica, together with other insoluble materials from the water. These substances have considerable influence on the structure and density of the rust coating on the metal surface. A loose, non-adherent coating under ordinary conditions, may accelerate the rate of corrosion; a uniformly dense and adherent coating may form an effective corrosion barrier and reduce the rate considerably.

<u>Influence of Hydrogen Sulfide.</u> Hydrogen sulfide when present in water makes the water acid and causes rapid corrosion, even in the absence of oxygen. It is mostly found in soils that contain anaerobic bacteria, in water contaminated with sewerage,



HIGHWAY SECTION LOCATED IN AREA OF ORGANIC REDUCING WATERSHEDS



HIGHWAY SECTION LOCATED IN AREA OF INORGANIC OXIDIZING WATERSHEDS

NOTE.
No culvert with less than 10 years service plotted Unless deterioration was significant.
o = Galvanized C M P
Δ = Asphalt Dip C M P
* = Calculated from estimated metal loss at time of inspection
+ = Culverts with calculated life in excess of 40 yrs plotted on 40 year ordinate

Figure 7. Comparison of culvert corrosion rates.

or in mineral water. In the presence of oxygen, sulfuric acid may be formed as a reaction product (1, 4).

SUMMARY

This study is based on a survey of the condition of 7,000 corrugated metal plate culverts located in one of the highway districts of the California Division of Highways and supplemented by spot checks throughout the state.

During this study, a geologist's pick was utilized as a form of a hardness tester to estimate the amount of culvert metal lost to corrosion. It has been found to be a rapid and practical tool for the inspection of metal culverts. This type of test was found to be more reliable than an observed evaluation of the condition of a culvert. It was not unusual to inspect 10 culverts per hour using a combination of observation and geologist's pick testing.

The reason for a lack of correlation between observation and destructive testing of the culverts was that the presence of rust was found to be an unreliable indicator of degree of corrosion. Generally, in various geographic locations the only conditions under which a tested and an initially observed estimate of culvert deterioration closely agreed was when the culvert was entirely corroded, perforated or new.

The over-all results of this study indicate that the service life of individual culverts is highly variable, depending upon the environment; and that the presence of continuous (or nearly so) water flow indicates a potentially corrosive area.

Also, it was found that the service life of culverts decreased as the percentage of soils classified as organic reducing and organic oxidizing increased. Conversely, when the number of watershed soils classified as inorganic oxidizing increased, the service life of the culverts increased.

A soil was not classified as an organic reducing type unless an odor of hydrogen sulfide could be perceived. Anaerobic bacteria (Sporovibrio desulfuricans) form hydrogen sulfide. Although laboratory tests were not performed to isolate and identify these

Figure 8. Rusted appearance of a culvert invert as a result of a corrosive flow.

organisms, it is felt that the environments identified as organic reducing could support anaerobic bacteria. Also, the physical characteristics of the watersheds identified as organic reducing in this study agreed with the physical characteristics of soils described by Starkey and Wight as those supporting anaerobic bacteria.

Since the purpose of this study was primarily to determine the condition of each culvert as fast as possible, no attempt was made to determine the exact material specification[1] under which the coating, galvanizing, or base metal of the particular pipe was furnished. It is therefore evident that the value in studying corrosive factors of the metals involved lies in gross statistical evidence rather than specific findings.

ACKNOWLEDGMENTS

This investigation of the corrosion of metal culverts was conducted as one of the activities of the Materials and Research Department of the California Division of Highways.

The authors wish to express their sincere appreciation to F. N. Hveem, Materials and Research Engineer of the Materials and Research Department, for his invaluable advice and direction during this study. Also, to the personnel of the California Division of Highways and those of the Materials and Research Department who extended their aid and cooperation during this study and especially to members of the Maintenance Department of the Division's District 1 who gave unstintingly of their time in determining the ages of the unidentified culverts.

Figure 9. Depicts the appearance of the invert of a culvert located in an alkali soil area.

[1] Such a determination was impractical since many of the metal pipes had been installed by various political subdivisions prior to the time the roads had been included in the State highway system. All corrugated metal pipes placed under the jurisdiction of the California Division of Highways are controlled by AASHO Designation M36 insofar as the base metal and galvanizing is concerned, and AREA specifications for bituminous coated metal pipe insofar as bituminous coating is concerned. This latter specification was adopted as a result of this study.

Figure 10. Corroded surface of a pipe contacting a corrosive backfill soil.

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Influence of Soil Characteristics on Deformation of Embedded Flexible Pipe Culverts

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● BASED ON observations of flexible pipe culverts under earth fills, it is generally conceded that pipe failure may be defined as a deformation (1, p. 70; 3, p. 9-10). Specifically, failure is that deformation beyond which the culvert ceases to function satisfactorily. Under load the horizontal diameter increases and the vertical diameter decreases such that the culvert assumes an approximately elliptical shape with the major axis horizontal. In extreme cases the pipe either collapses or is in a state of incipient collapse at failure. Collapse can only occur after the horizontal diameter reaches its maximum value. Rational design requires that the increase in horizontal diameter should be held below the maximum or critical value. In some installations, it is conceivable that excessive deformation of the pipe might adversely affect the conveyance characteristics of the pipe or might allow the soil above the pipe to settle excessively. Under such conditions, failure could still be described in terms of a maximum allowable increase in horizontal pipe diameter. In this case, the allowable increase might be less than critical, but as for failure by collapse, it is important to predict the increase in horizontal diameter of the pipe as a basis for design. M. G. Spangler of Iowa State College has proposed a formula for doing this (3, p. 29). This formula, often referred to as the Iowa Formula, is as follows:

$$\Delta x = \frac{K W_c r^3}{EI + 0.061 (er) r^3} \qquad (1)$$

where

Δx = increase in horizontal diameter of the pipe culvert (in.)
K = a parameter which is a function of the pipe bedding angle, α
(K = 0.083 for a bedding angle of 180)
W_c = vertical load per unit length of the pipe at the level of the top of the pipe (lb/in.)
r = mean radius of the pipe (in.)
E = modulus of elasticity of the material from which the pipe is constructed (psi)
I = moment of inertia of the cross-section of the pipe wall per unit length ($in.^4$/in.)

er = E' = a property of the soil which must be constant for any given soil according to Spangler's assumption in deriving the formula. (3, p. 28-29; 5, p. 45)

In this report er (or E') is referred to as the modulus of soil reaction.

The object of the investigation was to determine if the modulus of soil reaction is a function of any of the commonly recognized and easily measured soil properties. Clearly it would be uneconomical to determine values of this modulus from measurements on a test section or model for every culvert installation. Nevertheless, the modulus can be predicted for a specific installation by a test section or even by model analysis (6, p. 581), if the effort is justified. But more satisfactory is the use of model analysis to determine the relationship between the modulus and the more easily measured and more commonly recognized soil properties. This was the specific objective of the investigation.

Experimental data were collected from tests on a model soil-culvert system. A heavy box-like cell was constructed as shown in Figure 1. The ends of the cell were each lined with a rubber pressure diaphragm so that a simulated soil load could be applied by gas pressure. A particular soil sample was selected; then with the cell resting on one end and with the upper end removed, the soil was compacted in the cell under carefully controlled conditions. Since the cell was designed to hold exactly one cubic foot in volume it was an easy matter to determine the density of the compacted soil.

The upper end was then replaced and the cell was laid horizontally so that the bakelite window in the side of the cell was on top (Fig. 2). It was then possible to remove the bakelite window and force a model section of pipe into place in the cell. This operation was very sensitive in that slight misalignment caused considerable variation in the final results. To reduce misalignment a jig was constructed by means of which the model pipe section could be accurately positioned. Placement was accomplished by sucking soil from within the model pipe by a vacuum cleaner while the inside element of a jig bearing the model pipe section was forced downward until the pipe section was in place. The jig also provided for ejection of the model pipe section so that the jig itself could be withdrawn. This jig greatly improved the replicability of results. It was then possible to install a dial indicator gage mounted on ball bearings as shown in Figure 3. With the dial in place, the bakelite window was replaced, gas pressure lines were connected to both ends of the cell which were equipped with rubber diaphragms and the soil within the cell was subjected to gas pressure applied in increments (Fig. 4). With each increment of pressure a corresponding dial reading was taken and the results were plotted as a pressure-deflection curve.

In order to evaluate the modulus of soil reaction, the Iowa Formula may be worked backwards from known deflections and culvert loads to the corresponding value for the modulus. It is shown rewritten below in this proposed form.

$$E' = er = 1.36 \left(\frac{W_c}{\Delta x} \right) - 16.4 \left(\frac{EI}{r^3} \right) \qquad (2)$$

(The value for K has been assumed to be 0.083)

For average design the load on the pipe W_c may be assumed to be directly proportional to the height of fill and the diameter of the pipe (2, p. 424); $W_c = C'DH\gamma_t$ where

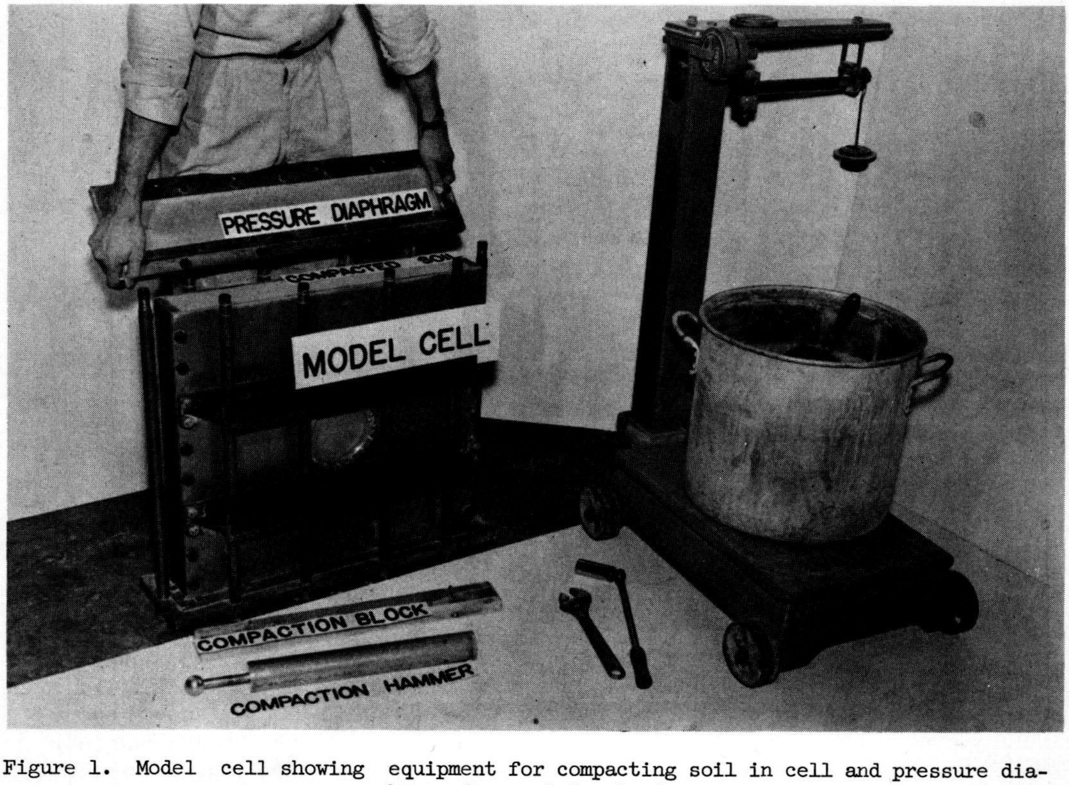

Figure 1. Model cell showing equipment for compacting soil in cell and pressure diaphragm for applying load.

C' = a constant, D = pipe diameter, H is the height of fill above the top of the pipe, and γ_t = a total unit weight of soil. In order to simulate these conditions on a model with the load supplied by an inflated membrane, an equivalent height of fill H is supplied by the pressure in the membrane or $H = \frac{p_v}{\gamma_t}$ where p_v = the vertical soil pressure at the level of the top of the pipe, or $p_v = pC_1$ where

p = diaphragm pressure

C_1 = the ratio of soil pressure at the level of the model pipe to the diaphragm pressure. C_1 is constant for a given soil in a given cell (see Fig. 5).

γ_t = total unit weight of soil.

Now by simply substituting these values in Eq. 2, the modulus becomes

$$E' = C\,D\left(\frac{p_v}{\Delta x}\right) - 131.2\left(\frac{EI}{D^3}\right)$$

where $p_v = \gamma_t H$ and C is the product of various constants.

For analysis on the model cell,

$$E' = CDC_1\left(\frac{p}{\Delta x}\right) - 131.2\left(\frac{EI}{D^3}\right) \tag{3}$$

This is the Iowa Formula rewritten to evaluate the modulus in terms of pipe diameter D, pipe wall stiffness EI, and the ratio of soil pressure to horizontal deflection $\frac{p_v}{\Delta x}$. Spangler's assumption that E' is a soil constant must be true if $\frac{p}{\Delta x}$ is a constant for any

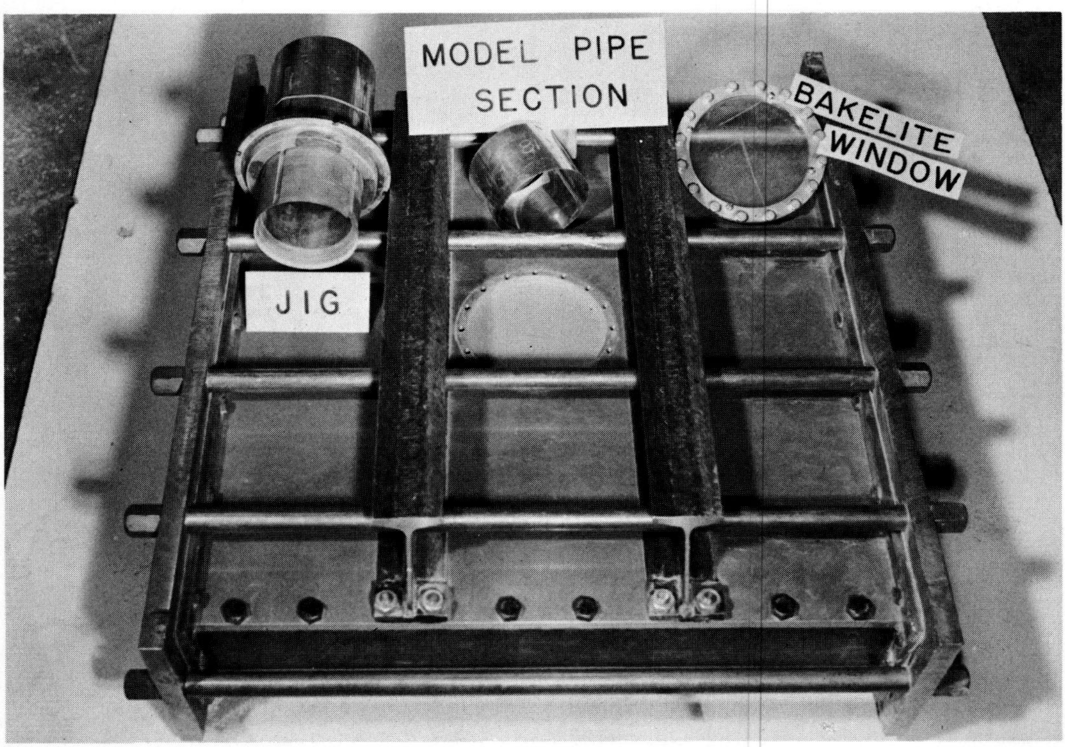

Figure 2. Jig for placing the model pipe section in place in the model cell (soil drawn from inside pipe section by a vacuum cleaner).

given pipe system. A cursory inspection of Figures 6 and 7 shows this to be the case.

When the pipe wall stiffness, EI, is varied, model tests show that the effect on E' is so small as to be negligible. This result is demonstrated by a typical test (see Figure 8) for which the following table applies:

TABLE 1

VALUES OF MODULUS OF SOIL REACTION, E', AS A FUNCTION OF CULVERT WALL STIFFNESS, EI FOR WHITE SILICON SAND

EI	E' (psi)		
	for C=1.36[a]	for C=0.95[a]	for C=0.88[a]
59 lb in.	2380	1780	1550
16.6 lb in.	2420	1810	1560
3.22 lb in.	2450	1810	1550

[a] C_1 = 0.18 in Eq. 3 for this particular model cell.

The table shows that E' is independent of pipe wall stiffness EI within the accuracy of the component measurements.

It may be concluded that the modulus of soil reaction for a flexible culvert is dependent on the soil only and may be assumed constant for any given soil. The dimension of E' lends further credence to this conclusion, for the dimension (lb in.$^{-2}$) is the same as the dimension for modulus of elasticity which is a property of the material only. If the modulus of soil reaction is similar to the modulus of elasticity, it should be possible to evaluate it by a simple stress-strain test such as the compression test.

It is interesting in Table 1 to note that even though E' is independent of EI, its

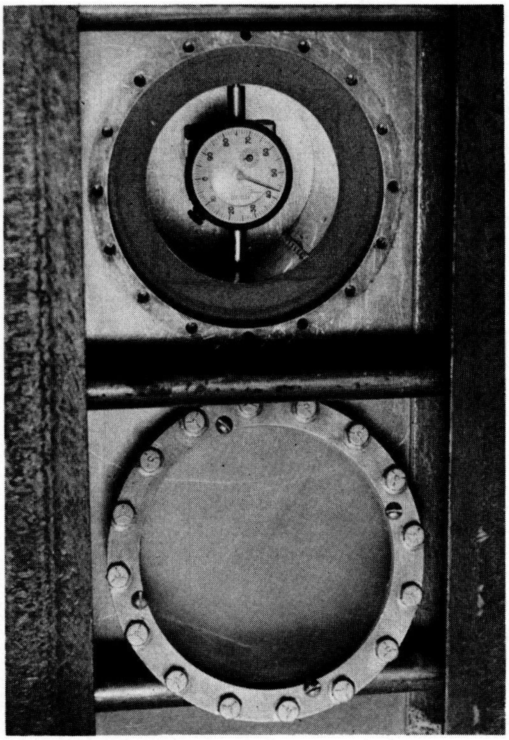

Figure 3. Dial indicator gage mounted on ball bearings within model pipe section.

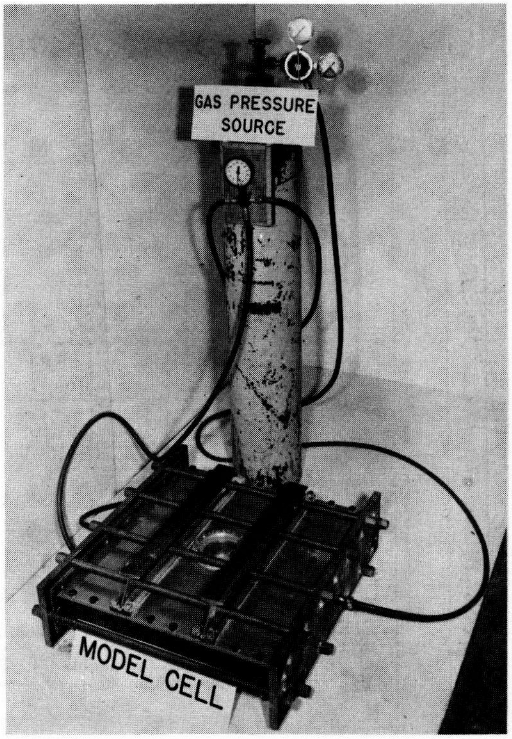

Figure 4. Assembly connected and ready for application of load.

absolute value is highly dependent on the constant C which in turn is dependent on a number of hard-to-evaluate factors such as the bedding angle which is unknown for a flexible pipe, the extent of projection condition or ditch condition, etc. For the design of most culverts under high fills, it appears advantageous to solve for both C and E' by

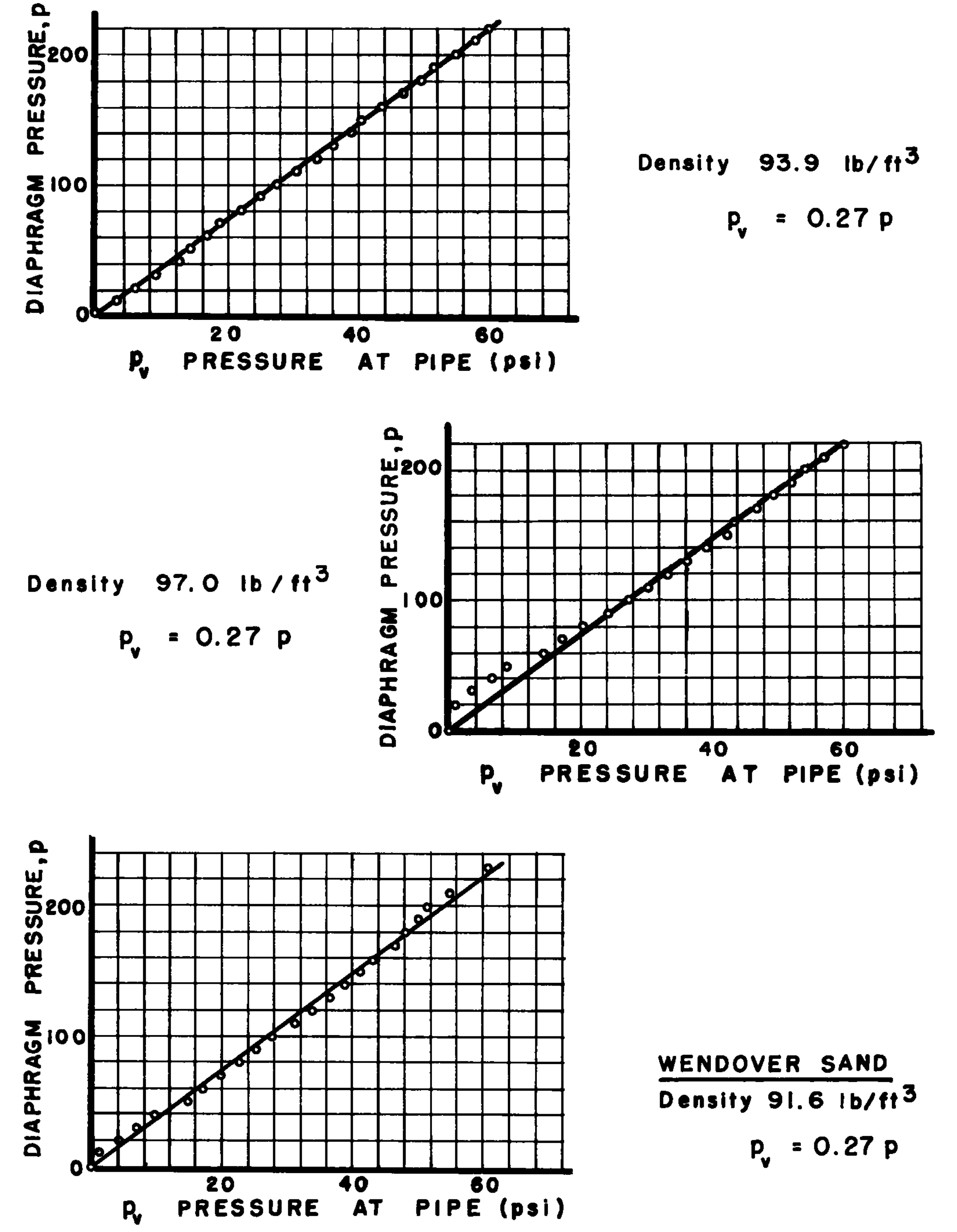

Figure 5. Diaphragm pressure required to develop soil pressure at the level of the top of the model pipe in Wendover sand at various densities.

plotting two or more model study curves varying EI (or D) as in Fig. 8, then by evaluating C and E' between any two curves by use of Eq. 3. If the resulting values of C and E' are used to predict culvert deflection the Iowa Formula becomes:

$$\Delta x = \left(\frac{C\, p_v}{E' + 131.2 \, \dfrac{EI}{D^3}} \right) D \qquad (4)$$

The soil constant problem has now been expanded to an evaluation of both C and E' for any given soil.

Evaluation of C

As is evident from Table 1, the constancy of E' is not sensitive to C. Even if a slightly incorrect value of C is used, the resulting calculated value of E' will still give good results in predicting Δx. A physical interpretation of this might include the following:

1. Flexible culvert will smooth out stress variations in the soil. For example, the bearing angle on the base will approach 180 deg as the culvert deforms regardless of the initial bearing angle.

2. The flexible culvert will tend to eliminate the difference between the settlement of the soil above and below it so that stresses tend to become symmetrical above and below the pipe. The model cell is designed on this assumption. Actually the assumption is not arbitrary because on the more carefully controlled projects, the flexible pipe is bedded on a good blanket of fill material.

3. The influence of pipe wall stiffness on the deflection is very small, therefore

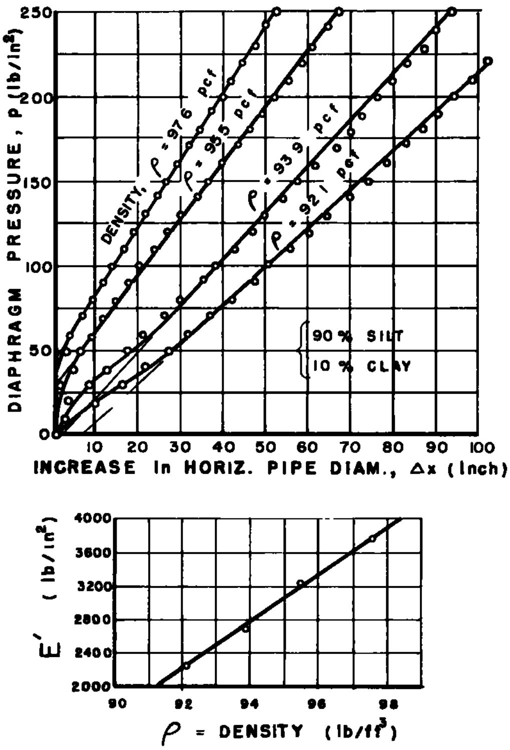

Figure 6. Pressure-deflection diagrams and E -density diagram for a mixture of 90 percent Bear River silt and 10 percent Trenton (Utah) clay.

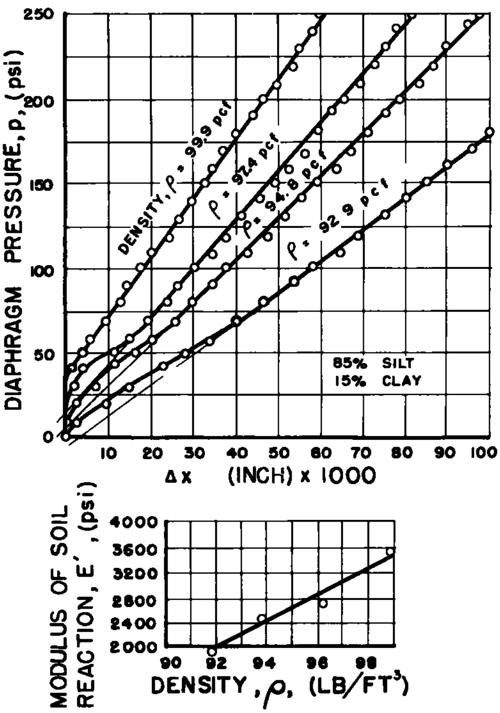

Figure 7. Pressure-deflection diagrams and E -density diagram for mixture of 85 percent Bear River silt and 15 percent Trenton (Utah) clay.

Δx is determined largely by the ratio of C to E' (see Eq. 4) rather than the absolute value of either C or E'. For example, in Table 1, E' varies from about 1,500 to 2,500 psi while $\left(131.2\,\frac{EI}{D^3}\right)$ varies from about 7 to 130 psi. Clearly Δx is more dependent on the ratio C: E' than the absolute values of C and E'.

It has been found that C may vary according to general soil types, but for a given type, it is relatively insensitive to other conditions such as compaction, stress, etc. For the sand analyzed in Table 1, either a value of C = 0.9 or C = 1 is good. A value of C = 1 has been assumed for the next paragraphs in which E' is investigated. The results appear to lose no accuracy by the assumption.

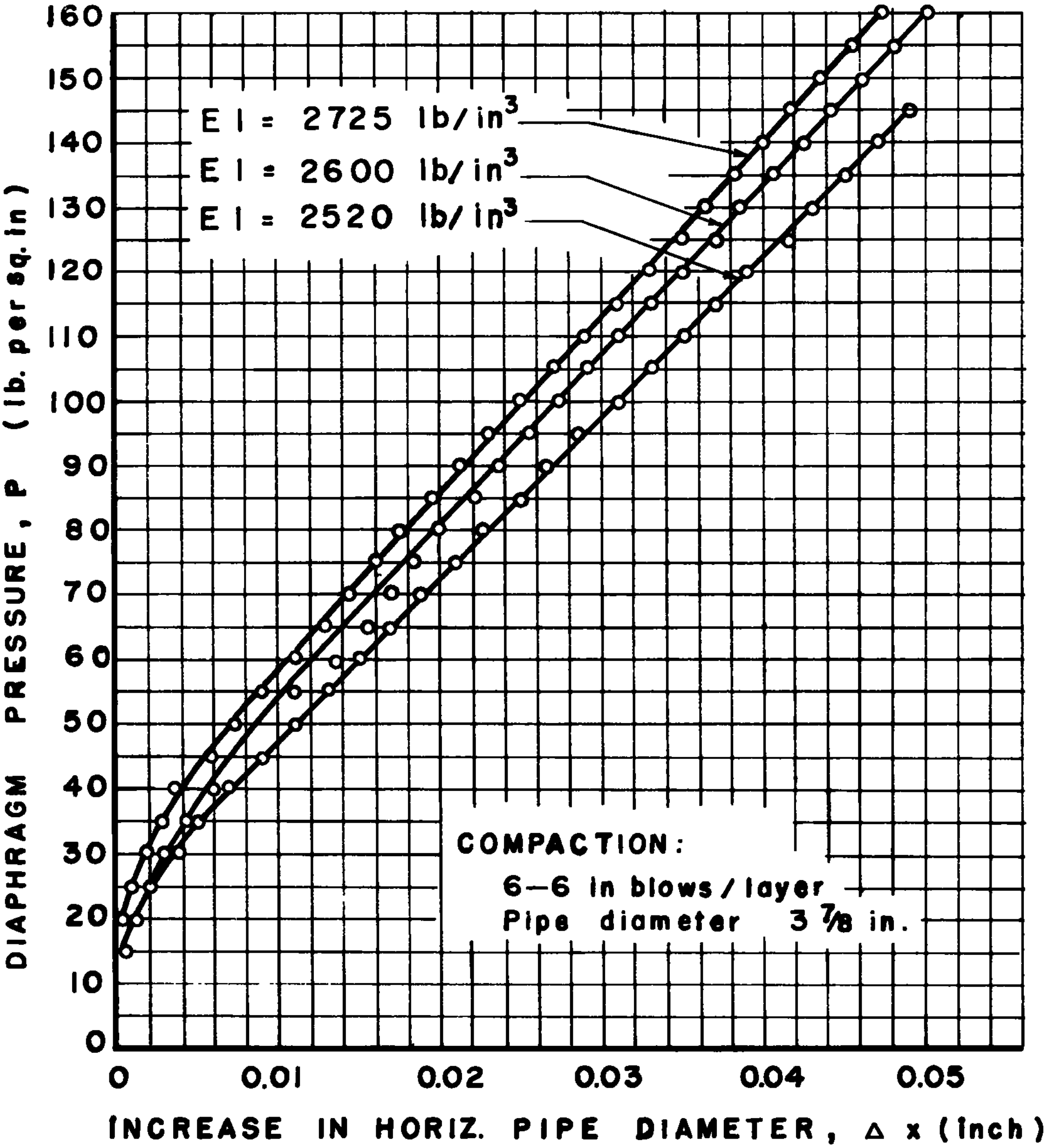

Figure 8. Pressure-deflection diagrams for white silica sand at varying values of the pipe wall stiffness factor, EI.

Evaluation of E'.

The modulus of passive resistance then remains the basic soil constant which must be determined. The most obvious conclusion from the pressure-deflection diagrams (Figs. 6 and 7) is that the soil density or degree of compaction is an important factor in determining E'. It appears in general that a linear relationship exists between soil density and E'. Some typical plots are shown in Figs. 6 to 9. Values of E' at low densities are the most likely to deviate from linearity, but this is due to void ratios in excess of critical and such low densities should possibly not be acceptable in culvert design. Critical void ratios will be discussed later.

Figure 10 shows how the slope of the E' density plot varies as a function of various soil types. In this case the soil types were synthesized by combining varying percentages of Bear River silt and Trenton (Utah) clay. E' was calculated by use of Eq. 3 with an assumed value of C = 1. A value of C_1 for the particular model cell was found to be 0.25 regardless of compaction and for all soil types tested in the series. This was determined by inserting an inflated innertube at the level of the top of the pipe, but without the pipe in place. The pressure in the innertube was measured as a function of load pressure in the membrane (see Fig. 5), then the ratio was calculated. The basic purpose of Figure 10 is to demonstrate how E' may be related to a compression modulus of soil as determined by simple compression tests.

Compression tests were run on silt-clay combinations. From compression tests it is common practice to plot the results as void ratio versus $\log_{10}$ of intergranular pressure. Such a curve usually plots as a straight line (4, p. 217). The slope is the compression modulus.

It should be noted that void ratio is an indication of the decrease in thickness of the sample, so it is an indication of strain in the sample. A compression curve for soil is effectively a stress-strain diagram with the stress plotted on a log scale so that the resulting plot will be a straight line. Just as the slope of the stress-strain diagram within the range of elasticity is the modulus of elasticity, so the slope of the compression diagram is in effect a compression modulus. That it is related to the modulus of soil reaction, E', for culverts is easily demonstrated. Figure 9 shows the modulus, E', as a function of soil density; therefore, it is necessary to plot the compression diagrams as a function of density likewise. This is possible since density is inversely proportional to void ratio and may be determined directly from it. Ordinarily the negative slope of the compression curve is computed and is designated as the compression index, C_c. This is defined as the rate of change of void ratio (or strain) with respect to the log of stress. Such an index is just the inverse of the type of quantity which one would define as a compression modulus. A plot of the compression modulus, $1/C_c$, as a function of soil type is shown in Figure 11. It is immediately apparent that the E'-density diagram and the $1/C_c$ diagram are related. As a matter of fact, the relationship is almost 1000 to 1 for the particular case shown; or

$$1000\left(\frac{1}{C_c}\right) = \frac{d\,(E')}{d_\rho}$$

By integrating the equation above

$E' = \left(\frac{1000}{C_c}\right)\rho$ + constant. When E' = 0, the constant $= \frac{1000}{C_c\,\rho_o}$ where ρ_o is the effective density of the soil at no soil pressure.

$$E' = \frac{1000}{C_c}\;(\rho - \rho_o)$$

The limits in the above equation are found from Figure 9. It would be very difficult to measure the density of the soil at no intergranular stress, but Figure 9 reveals that the value can be determined approximately from the intersection of the E' density lines with the E' = 0 line. It should be pointed out again that the low density values of E' are not actual since linearity ceases at low densities. For this particular diagram it is evident that ρ_0 varies within a rather narrow range of about 86 to 88 pcf depending on the soil. For any particular soil type a value of ρ_0 can be used as a constant.

So far this analysis has only been applied to sand, silt, and the combinations of silt and clay described above. There is a need to expand the analysis to include other soils to verify the theory. Also there is a need to evaluate the numerical factor relating E' to a soil compression modulus. The value of 1000 used here seems to be adequate for these tests, but there may be some variation in other soil types.

Figures 6 and 7 show a peculiarity that is common to most load-deflection diagrams. For the high density tests, the initial portion of the plot is concave down in such a fashion that the "y-intercept" for the straight line portion of the plot is a positive pressure. For the low-density tests, on the other hand, the initial portion of the plot is concave up and the "y-intercept" is a negative pressure. Tests show that this is true of the prototype as well as the model. The best explanation seems to be based on the concept of critical void ratio. If the soil is very loose, shearing strain or differential movement causes the soil grains to densify. But any densification tends to relieve the intergranular stresses. In order to maintain equilibrium, the stresses must be developed

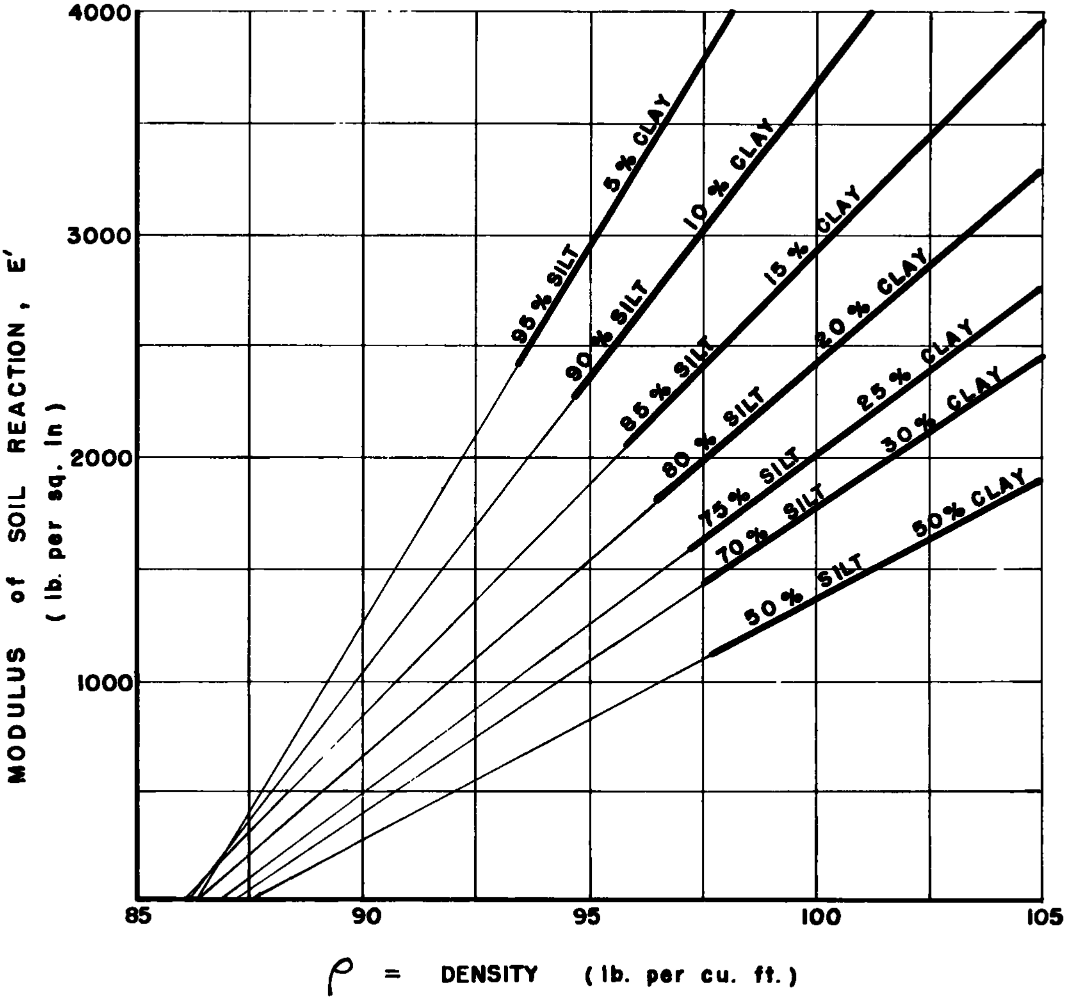

Figure 9. Plots of the modulus of soil reaction as a function of the soil density (so called E -density curves) for various combinations of Bear River silt and Trenton (Utah) clay.

by increased strains; so the relationship of strain to stress is greater while the soil is loose. On the other hand, if the soil is very dense, shearing strain causes the soil grains to roll over each other and to increase the volume of the soil mass. But such tendency to increase volume is resisted by the adjacent soil grains and excessive stresses are developed. For equilibrium these soil stresses must be relieved, but that can only be accomplished if the strains are relatively less. Of course, after the soil has generally shifted, the volume reaches an equilibrium point and the load deflection curve continues on as a straight line. The specific volume at which there is neither a tendency to increase nor to decrease during shear may be described in terms of critical void ratio. If the void ratio of the soil exceeds its critical value (that is, if the density is less than its critical) the actual deflection of the culvert will be greater than predicted. Since this is on the unsafe side in culvert analysis, a sure way to avoid this problem is to specify that the fill shall be of greater than critical density. With a density greater than critical, the reverse is true and the actual deflection of the culvert is less than predicted. This is on the safe side. If the project is of such magnitude that the deflection must be predicted more accurately, then the Iowa Formula should be modified to include a term which accounts for the "y-intercept" in the load-deflection curves.

The water content of soil was not a variable in the above considerations. Since the purpose of most culverts is to carry water, the soil adjacent to the culvert will probably be saturated part or all of the time. Work is yet to be done on the effect of water content, but it should be pointed out that most fills are placed dry or at optimum moisture content and most of the pipe deflection occurs during construction. For granular soil around the pipe, water does not alter the soil characteristics other than the vertical soil pressure, p_v which has no effect on E'. For a plastic soil the conditions of failure are entirely different. As the soil is saturated the pressures on the pipe approach hydrostatic pressures. In such event, the pipe would not continue to increase in horizontal diameter, but would tend to become circular again. For this case, some method of defining failure should be sought which is not based on deformation alone.

On the evidence that the modulus of passive resistance is a property of soil only, and that it can be readily related to the compression index for a given soil, it should be possible with a minimum of additional tests to arrive at the required relationships so that the deflection of a culvert can be predicted from a simple compression test in the laboratory.

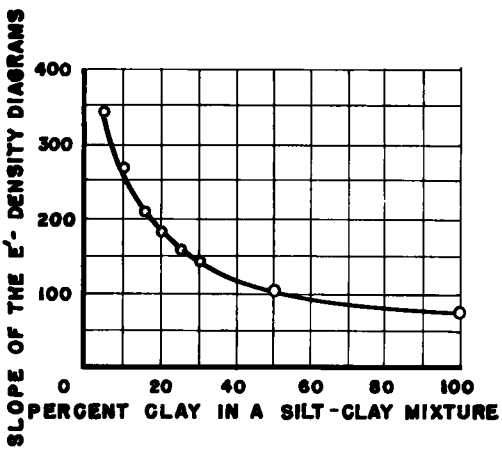

Figure 10. Slope of the E -density curve as a function of percent silt.

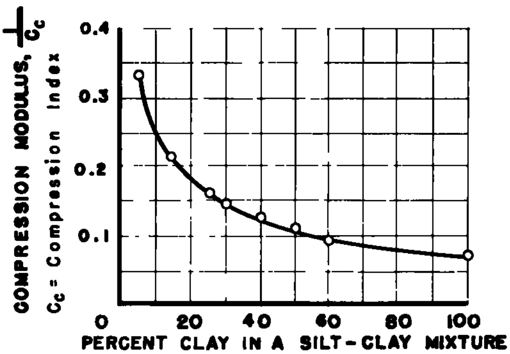

Figure 11. Compression modulus, $\frac{1}{C_c}$, as a function of the percent silt where C_c is the compression index of the soil as determined by a compression test.

Note: The shapes of the plots in Figs. 10 and 11 are so nearly the same as to show that the modulus of soil reaction, E', can be determined from the compression index of a soil.

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HRB: OR 263

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The NATIONAL RESEARCH COUNCIL was established by the ACADEMY in 1916, at the request of President Wilson, to enable scientists generally to associate their efforts with those of the limited membership of the ACADEMY in service to the nation, to society, and to science at home and abroad. Members of the NATIONAL RESEARCH COUNCIL receive their appointments from the president of the ACADEMY. They include representatives nominated by the major scientific and technical societies, representatives of the federal government, and a number of members at large. In addition, several thousand scientists and engineers take part in the activities of the research council through membership on its various boards and committees.

Receiving funds from both public and private sources, by contribution, grant, or contract, the ACADEMY and its RESEARCH COUNCIL thus work to stimulate research and its applications, to survey the broad possibilities of science, to promote effective utilization of the scientific and technical resources of the country, to serve the government, and to further the general interests of science.

The HIGHWAY RESEARCH BOARD was organized November 11, 1920, as an agency of the Division of Engineering and Industrial Research, one of the eight functional divisions of the NATIONAL RESEARCH COUNCIL. The BOARD is a cooperative organization of the highway technologists of America operating under the auspices of the ACADEMY–COUNCIL and with the support of the several highway departments, the Bureau of Public Roads, and many other organizations interested in the development of highway transportation. The purposes of the BOARD are to encourage research and to provide a national clearinghouse and correlation service for research activities and information on highway administration and technology.