MECHANICAL COMPACTION OF SOILS FOR ENGINEERING PURPOSES

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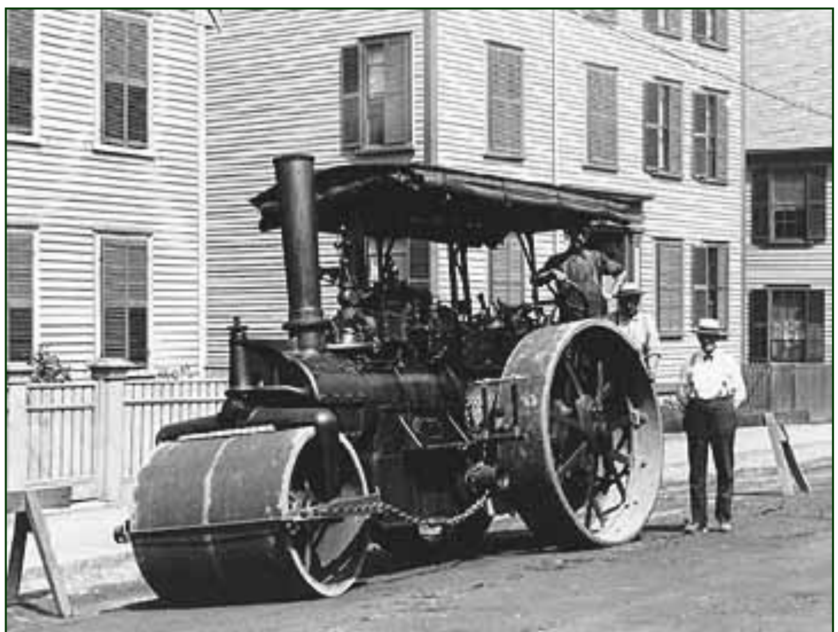
for the course

GE 441 Geotechnical Construction Practice

Part 1

ORIGINS OF MECHANICAL COMPACTION



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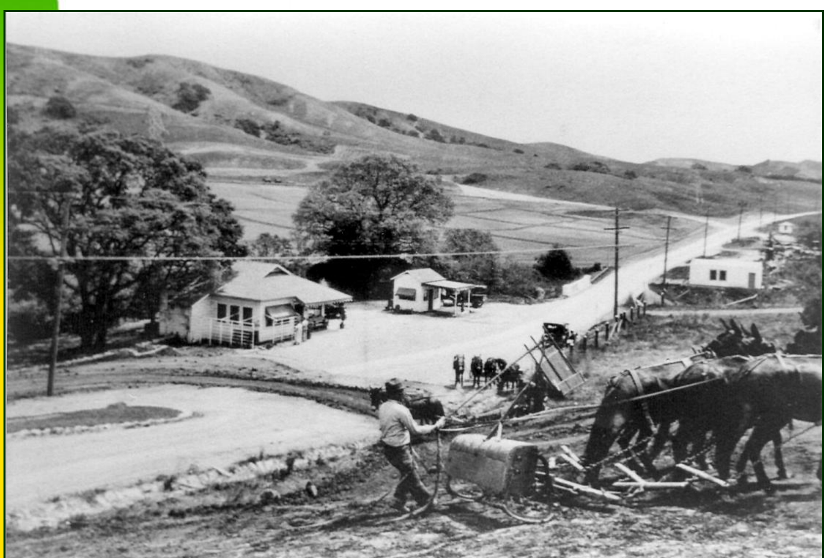
THE FRESNO GRADER



- **Abajiah McCall** invented the horse-drawn dirt bucket scrapper in Fresno County, California in 1885.
- It became known as the **"Fresno Scrapper"** and was widely employed as the prime earth moving device until the widespread advent of self-powered scrappers in the 1930s.

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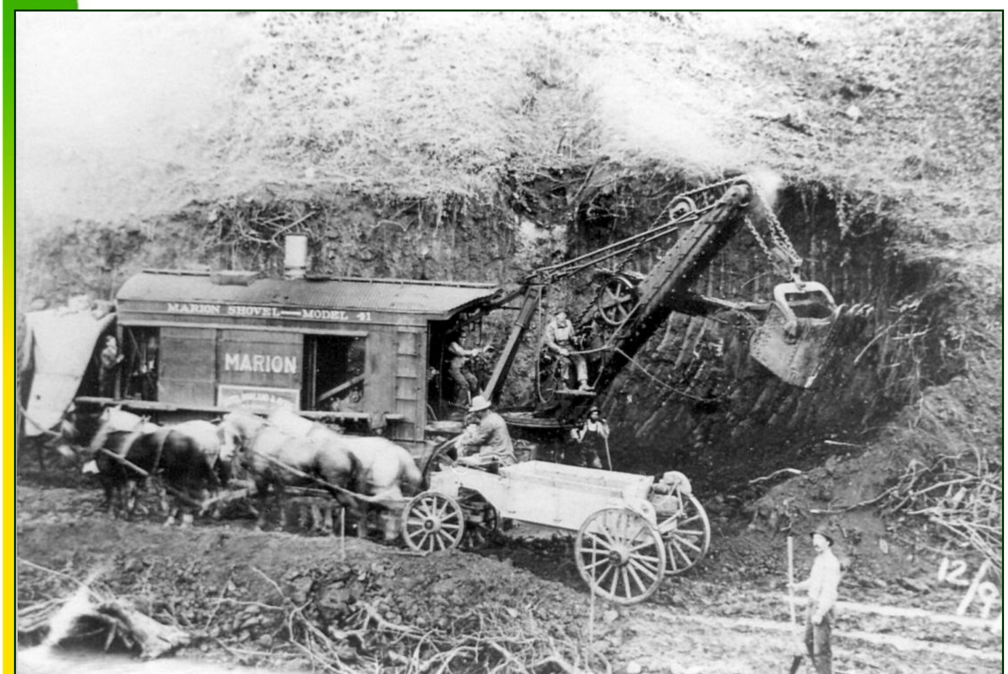
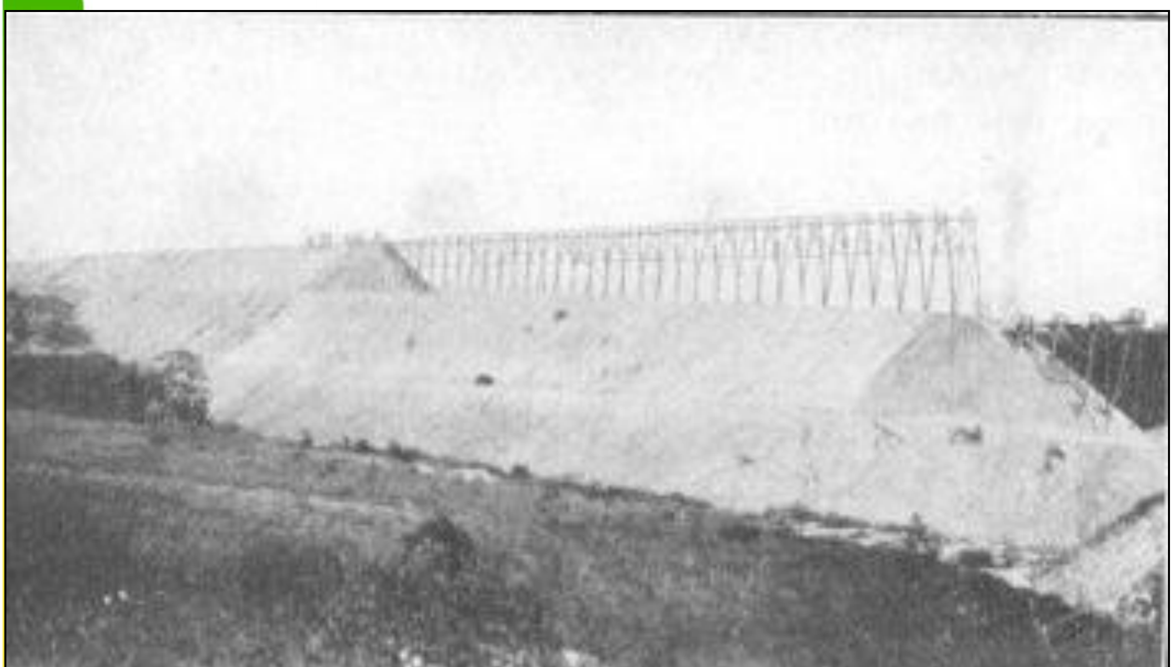
- **Above left: 10-horse team pulling an elevating grader to load hopper dumping wagons during construction of the Central Reservoir for the People's Water Co. in Oakland, California in 1909. Note old Buffalo-Springfield steam roller compacting the dam's embankment, in left background**

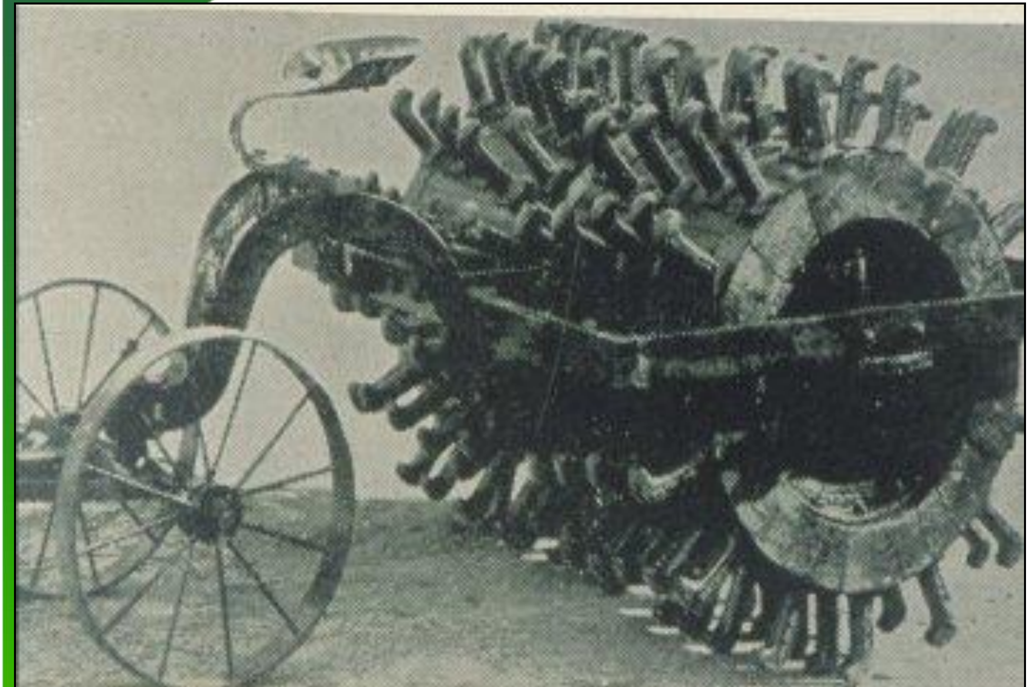


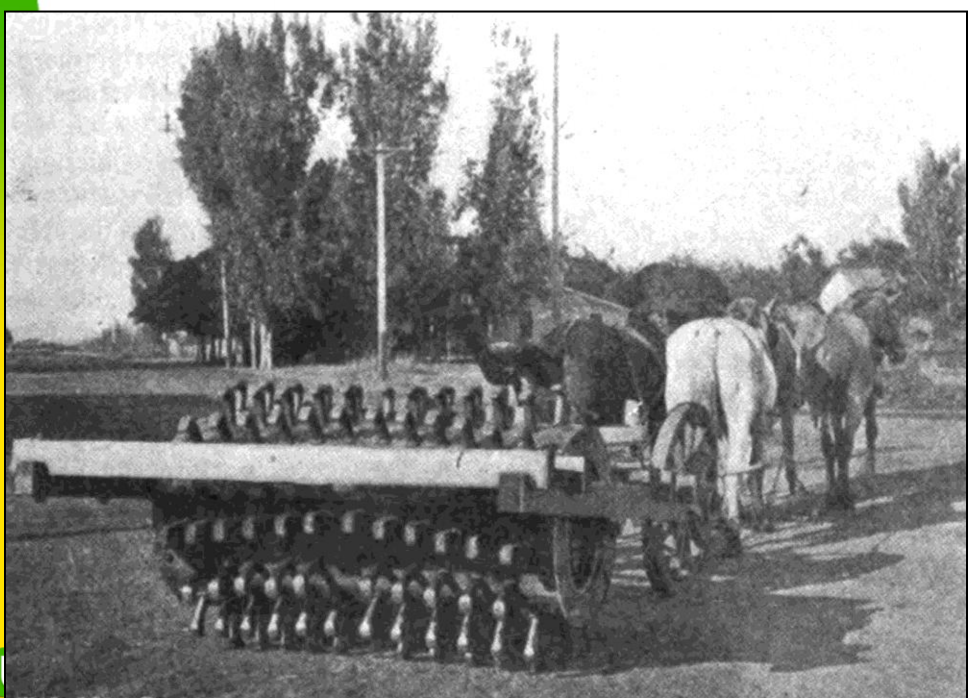
- **Below Left: Marion shovel loading a hopper dumping wagon at the San Pablo Dam site of the East Bay Water Company in 1920, in Richmond, California. At 220 ft high with a volume of 2.2 million yds^3 it was the highest and largest earth dam in the world when completed in 1922.**



"Load Compaction" of Trestle Fills

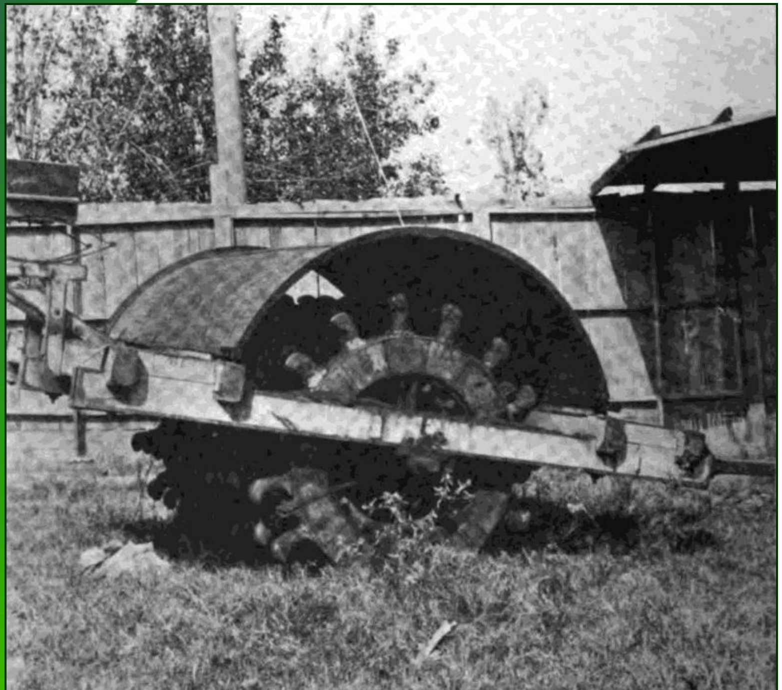
- In the early days large embankments were constructed by side-dumping rail cars or wagons from temporary wooden trestles, as shown at left.
- Engineers assumed that, after placement and infiltration by rain, the soil would *'compact'* under its own dead load.

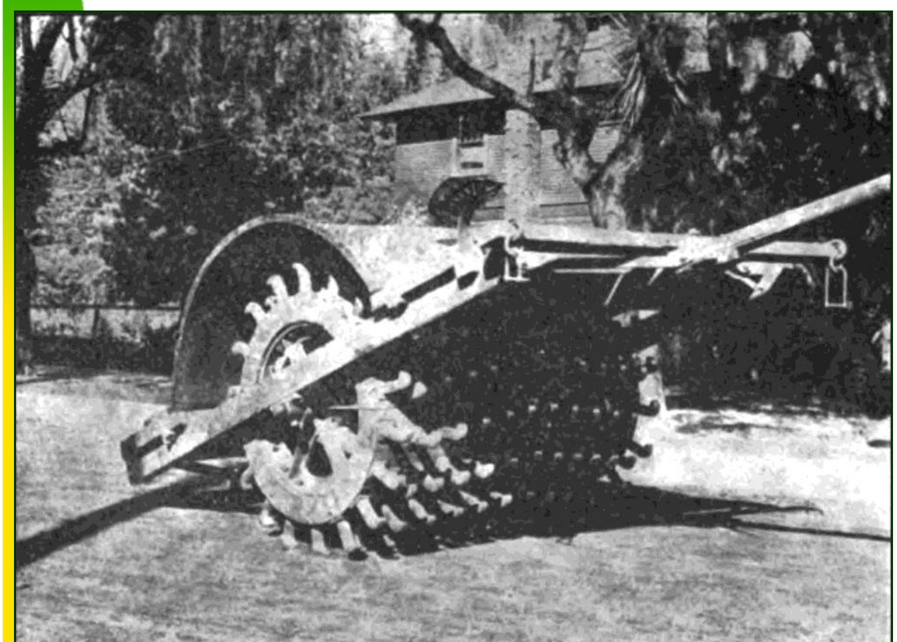




The first sheepsfoot rollers

- The first sheepsfoot roller was built in Los Angeles in 1902, using a 3-ft diameter log studded with railroad spikes protruding 7 inches, distributed so the spikes were staggered in alternate rows.
- This layout was soon modified to increase weight and efficiency, initially by increasing its length to 8 ft.
- Note the leading wheels on the early models shown here, absent later.
- The roller's weight was then increased to about 5000 lbs by filling them with sand and water (drained when moved).
- The 7-in spikes were enlarged to a contact of area of 4 sq inches. This increased the load bearing on each spike to 300 lbs, or about 75 psi contact pressure
- Marketed as the "Petrolithic Paving Tamper," it was built by the Killefer Manufacturing Co. of Los Angeles.





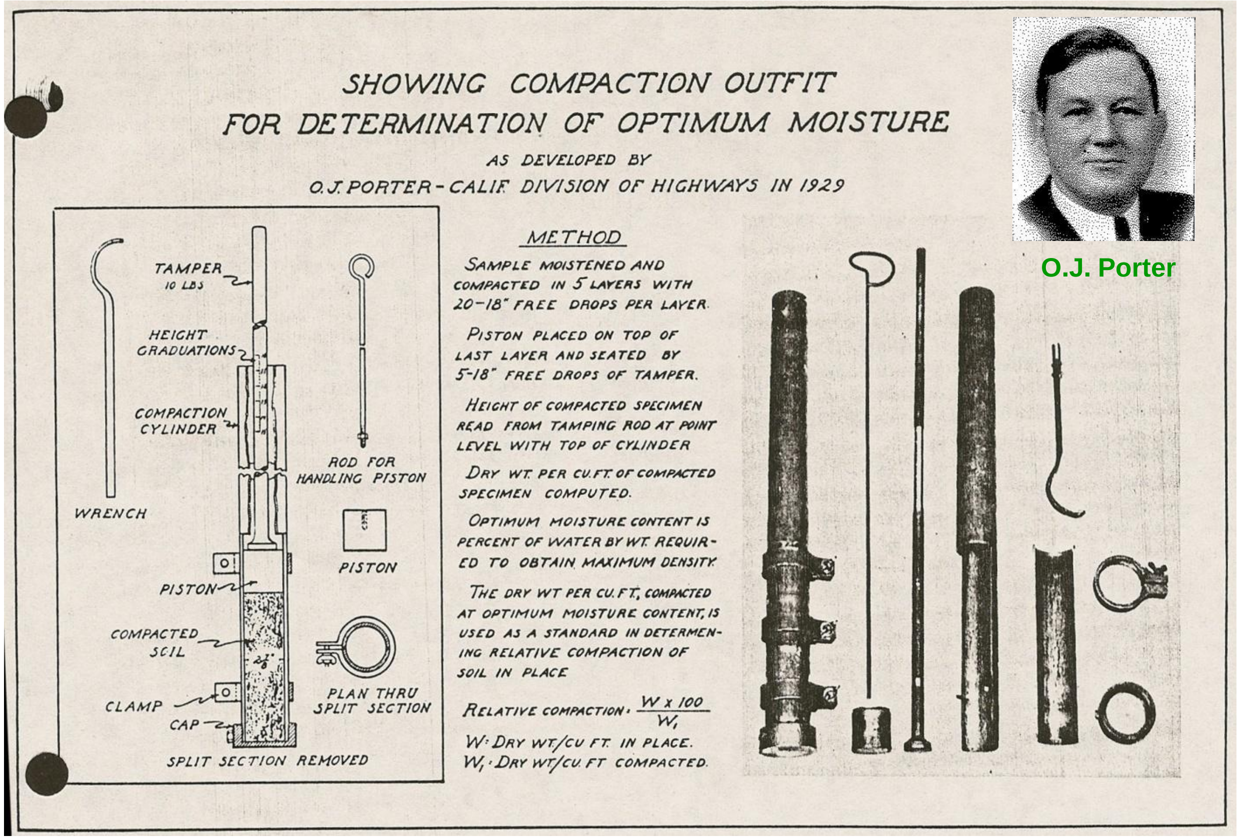
"Fitzgerald Rollers" 1906-23

- The roller was patented by **John W. Fitzgerald** in 1906, who worked for Walter and Harbert Gillette, owners of the Petrolithic Paving Co. of Los Angeles
- It was modified with a counter-balanced tow frame and hemispherical fender, is was manufactured by the Killefer Mfg. Co. of Los Angeles and marketed nationally as the "**Fitzgerald Roller.**"
- The number of spikes was reduced to either 10 or 11 per row, to bring the contact pressure up to 100 psi.
- It was first used to compact an embankment dam by Bent Bros Construction in El Segundo, CA in 1912.
- Thoughtful imitations soon appeared, and when the patent expired in 1923, it was not renewed.

First dams compacted with sheepsfoot rollers

- **The first earth embankments compacted with sheepsfoot rollers were the Lake Henshaw Dam in southern California in 1920-23 for the Vista Irrigation District in San Diego County, shown at left. This was followed in 1926 by Philbrook Dam for PG&E by R.G. Letourneau, and the Puddingstone Dam for the LACoFCD in 1925-27, using a new roller patented by contractor H.W. Rohl that employed ball-shaped heads.**
- **The first earth dam compacted by sheepsfoot roller for a federal agency was Echo Dam in Utah for the Bureau of Reclamation in 1928.**
- **The sheepsfoot roller's narrow spikes induced *kneeding compaction,* critical for densifying clayey soils.**

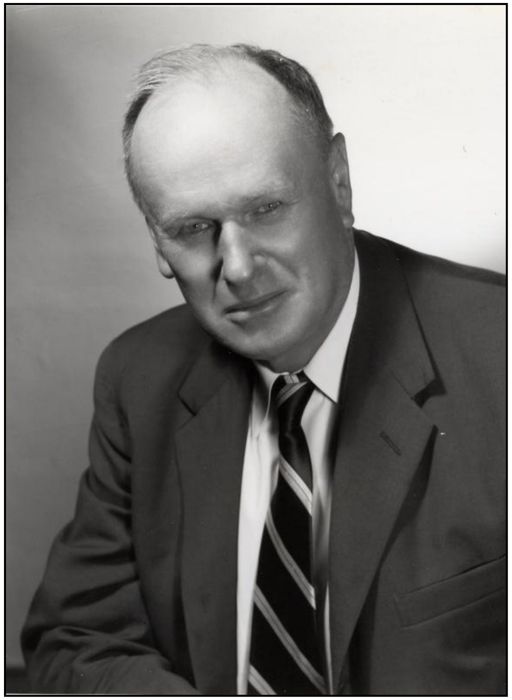
First compaction test procedure (1929)



O.J. Porter

- The first published standard for testing the mechanical compaction of earth was the California State Impact Method, or “California Impact Test.” It was developed in 1929 by O. James Porter, PE (1901-67) of the California Division of Highways in Sacramento.
- It presented a procedure for ascertaining the in-place wet density of aggregate baserock or compacted soil, and the preparation of a wet density versus soil moisture content curve (similar to what Ralph Proctor developed a few years later).
- The 216 test uses wet density as the measurement standard and has been modified six times since its original adoption in 1929. The current version of the test is referred to as California Test 216 – “Method of Test for Relative Compaction of Untreated and Treated Soils and Aggregates.” It employs energy input of 37,000 to 44,000 ft-lbs/ft^3 of soil.

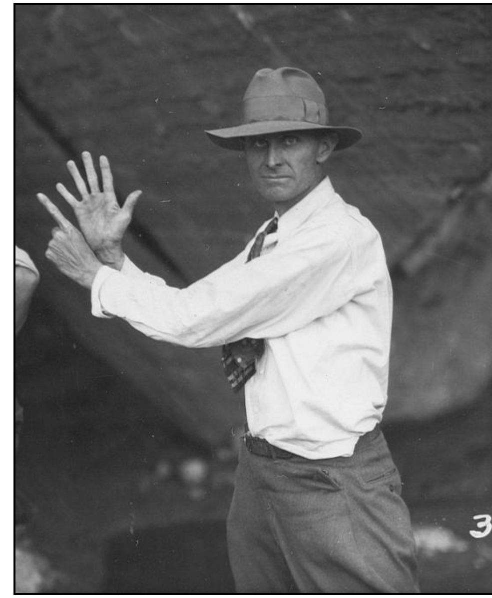
Ralph Proctor of the Proctor Compaction Test



Ralph R. Proctor, PE (1894-1962)

- **Ralph Roscoe Proctor** joined the Los Angeles Bureau of Waterworks & Supply in 1916 (which was absorbed into the Department of Water & Power in 1931), after studying engineering at USC for two years (he never completed his college degree).
- He served in Co. E. Of the 23rd Engineers in Europe during the First World War, constructing railroads.
- Proctor returned to Los Angeles and rejoined the Department of Water & Power as a field engineer. He was the resident engineer for the ill-fated St. Francis Dam during its construction and the post-failure surveys in 1928.
- He gained world renown for his work in developing the soil compaction test that bears his name in 1933, while working as resident engineer on the **Bouquet Canyon Reservoir** embankments, the replacement structure for St. Francis.
- From 1933 until his retirement in 1959 he was in charge of design, construction, and maintenance of all dams in the LADWP system.
- In 1948 Proctor authored four papers for the Second International Conference on Soil Mechanics in Rotterdam, including one titled *The Elimination of Hydrostatic Uplift Pressures in New Earthfill Dams*, considered one of the pioneering papers on a subject dear to the hearts of LADWP engineers who lived through the humiliation of the St. Francis Dam disaster.
- His last project for LADWP was as the resident engineer for the construction of the Baldwin Hills Reservoir in 1953-54, which failed 14 months after his death, in December 1963. He joined ASCE in 1927, becoming a Fellow and Life Member.

Dry Density Compaction Tests



Ralph Proctor was the resident engineer for the ill-fated St. Francis Dam during its construction in 1924-26. This led to his role in developing a method for evaluating soils compaction as the resident engineer for the Bouquet Canyon Dams.

- **Ralph Proctor** was a field engineer on the Bouquet Canyon Dams in 1932-34. The Construction Superintendent was H.L. Jacques.
- Jacques asked Proctor to devise a method of testing the compacted fill so the Los Angeles Dept of Water & Power could demonstrate to the world that they were constructing the safest dam possible.
- Note use of horses as well as a dump truck (in background) to pull the sheepsfoot rollers.

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PROCTOR'S FOUR ARTICLES in 1933

Engineering News-Record

Vol. 111 | New York, August 31, 1933 | No. 9

First of Four Articles on the Design and Construction of Rolled-Earth Dams

Fundamental Principles of Soil Compaction

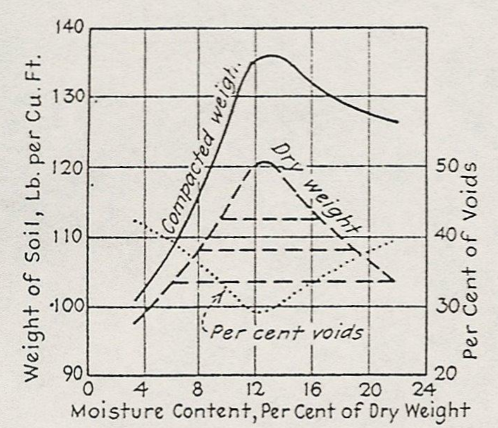
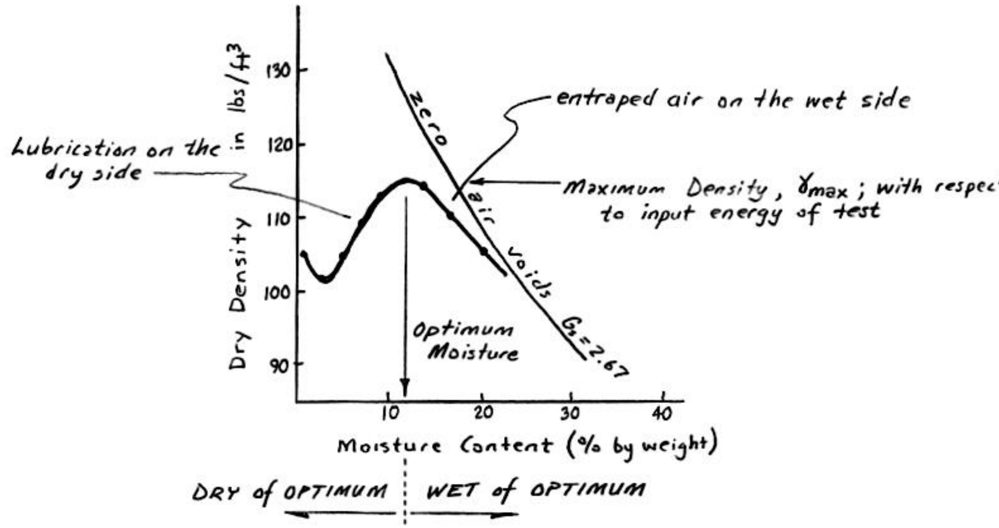


Fig. 2—Graph showing the effect of moisture content on the compacted weight, dry weight and voids of a soil when compacted by a particular method.

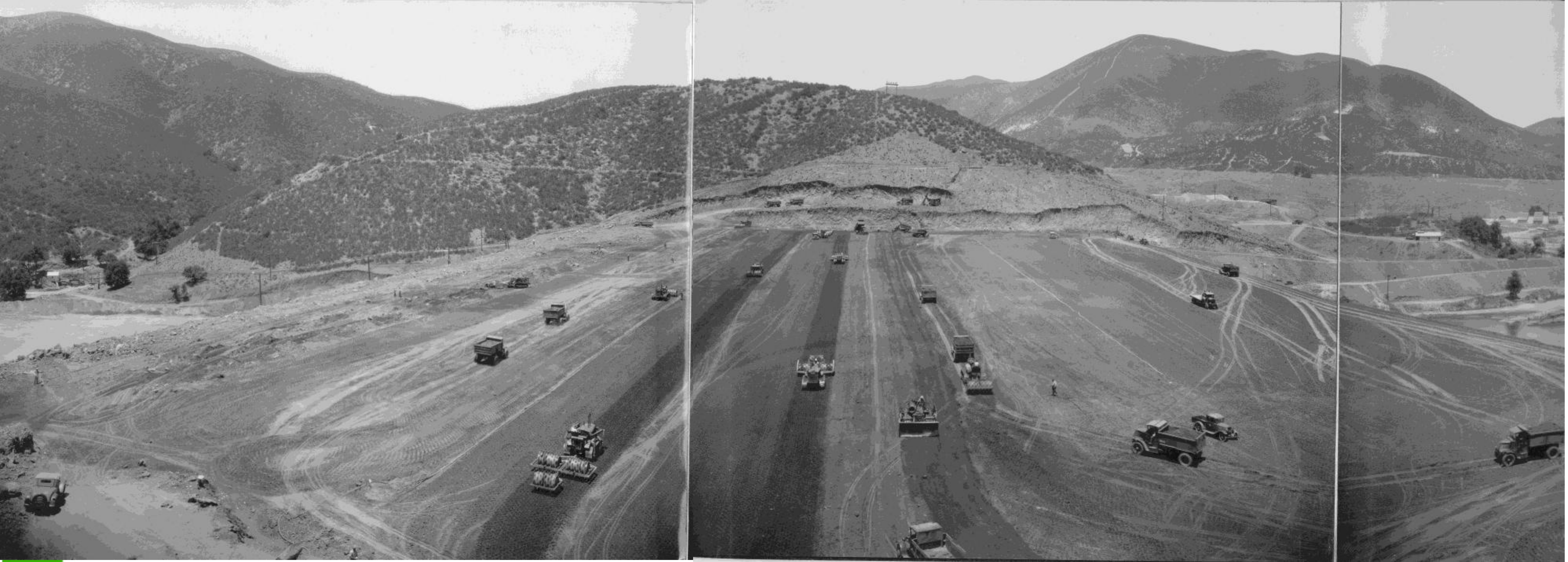


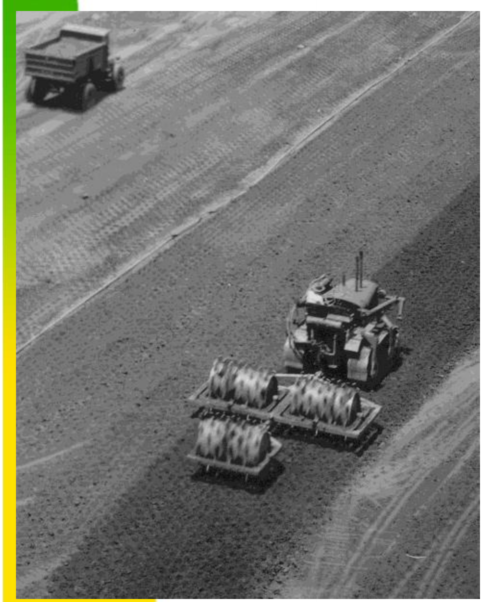
- Ralph Proctor devised an alternative method to California Test 216 introduced by the California Division of Highways in 1929, which measures the *maximum wet density* ('compacted weight,' shown above left), and controls the compactive effort based on the total weight, not the volume, of the test sample (Caltrans still uses this alternative test procedure).
- The primary advantage of Proctor's procedure is that the test results could be computed onsite, as evaporation of the compacted sample is not necessary. This allowed immediate adjustment of the soil water content, which was the *critical variable* the contractor needed to know.

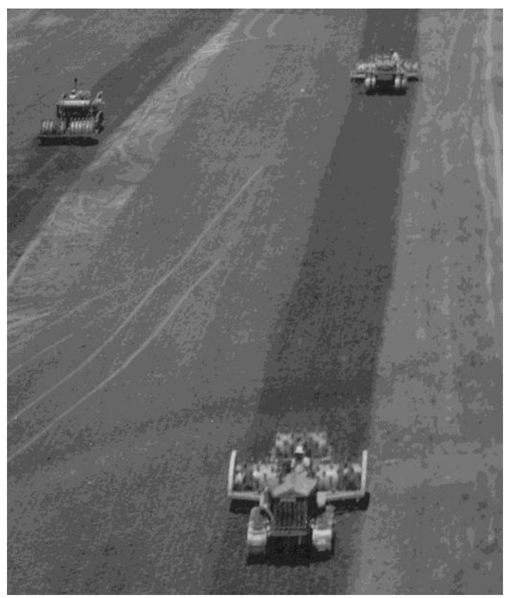
The Standard Proctor Compaction Test (1933)

Standard Proctor Compaction Mold with collar extension and drop hammer in cylindrical sleeve

- The original Proctor Compaction Test of 1933 used cylindrical mold 4 inches in diameter and 4.6 inches high, with a removable mold collar 2.5 inches high. The mold volume is 1/30th cubic foot
- A 5.5 pound hammer, 2 inches in diameter, was pulled upward and allowed to free-fall 12 inches, onto the soil (5.5 ft-lbs per blow)
- The soil was compacted in three lifts, with an average thickness of 1.33 inches/lift.
- 25 blows were exerted per lift, which equals 25 x 5.5 = 137.5 ft-lbs. The total input energy for the three lifts was 3 x 137.5 = 412.50 ft-lbs on a soil sample with a volume of 1/30th cubic foot. This equals 12,400 ft-lbs of compactive energy per cubic foot of soil
- Designated ASTM Test D698 (adopted July 1950), AASHTO T99 (adopted 1950), and BurRec E11 (adopted 1947).

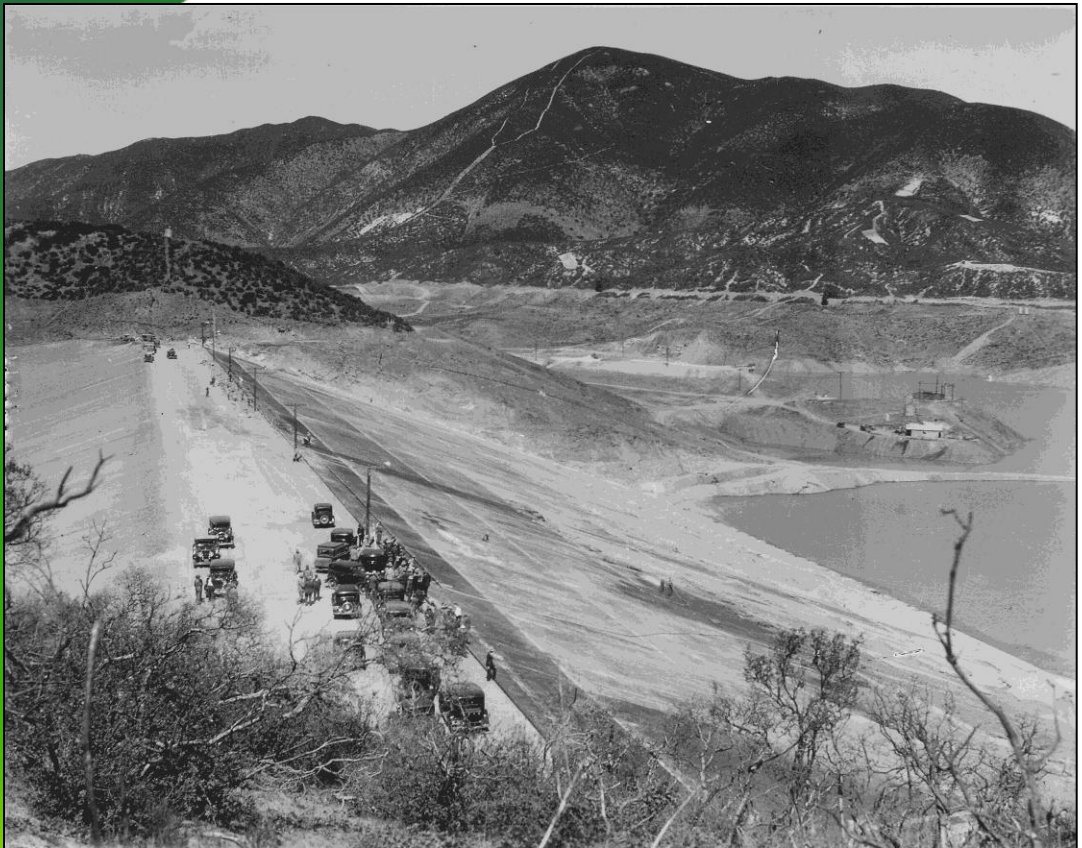


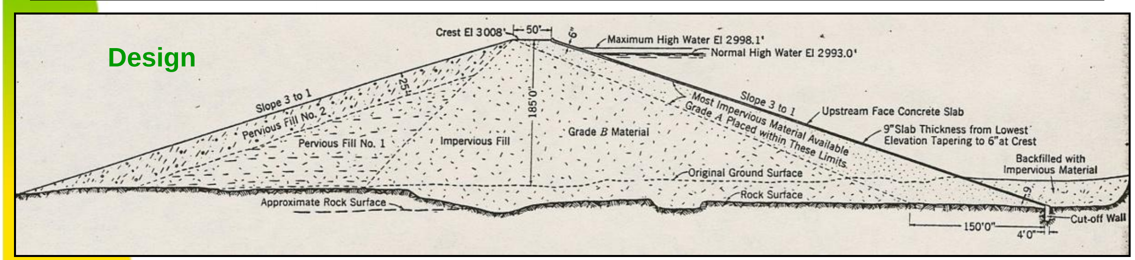


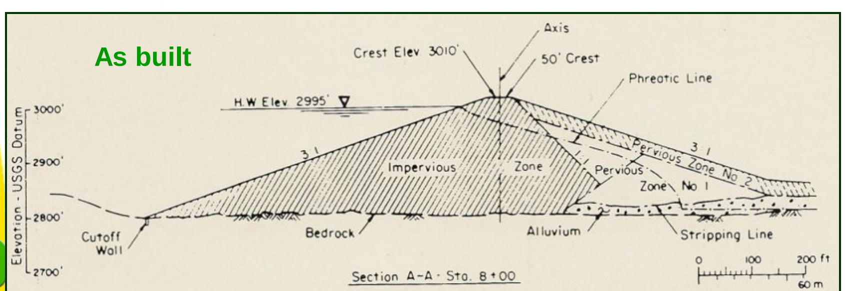


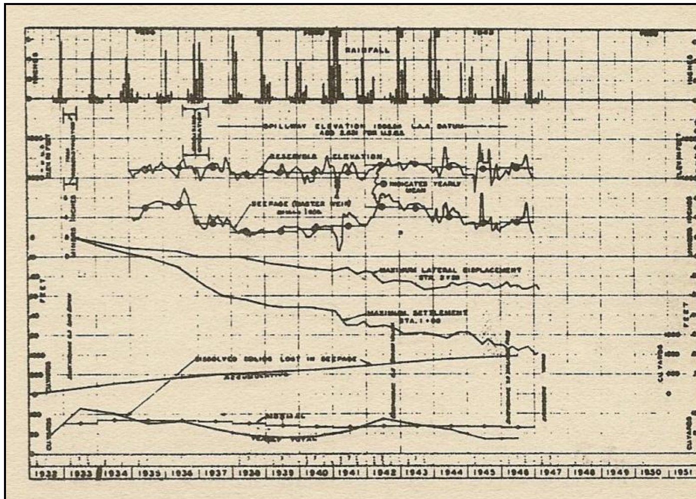
- The two Bouquet Canyon zoned fill embankments were constructed by the Los Angeles Department of Water & Power between 1932-34 to replace the St. Francis concrete dam, which failed in 1928.
- These were the first embankments constructed using the standard Proctor Compaction Test

- Upper - The main embankment of **Bouquet Canyon Dam** was completed in March 1934, with concrete paving of the upstream face.
- Middle - Original design for main embankment
- As-built section thru main embankment – but in opposite direction
- Below right – Long-term monitoring of embankment









Form used to show 20 years record of rainfall, reservoir stages, seepage, lateral displacement and settlement of crest of dam, and dissolved solids in seepage water, together with earthquake, repair, grouting and related data.

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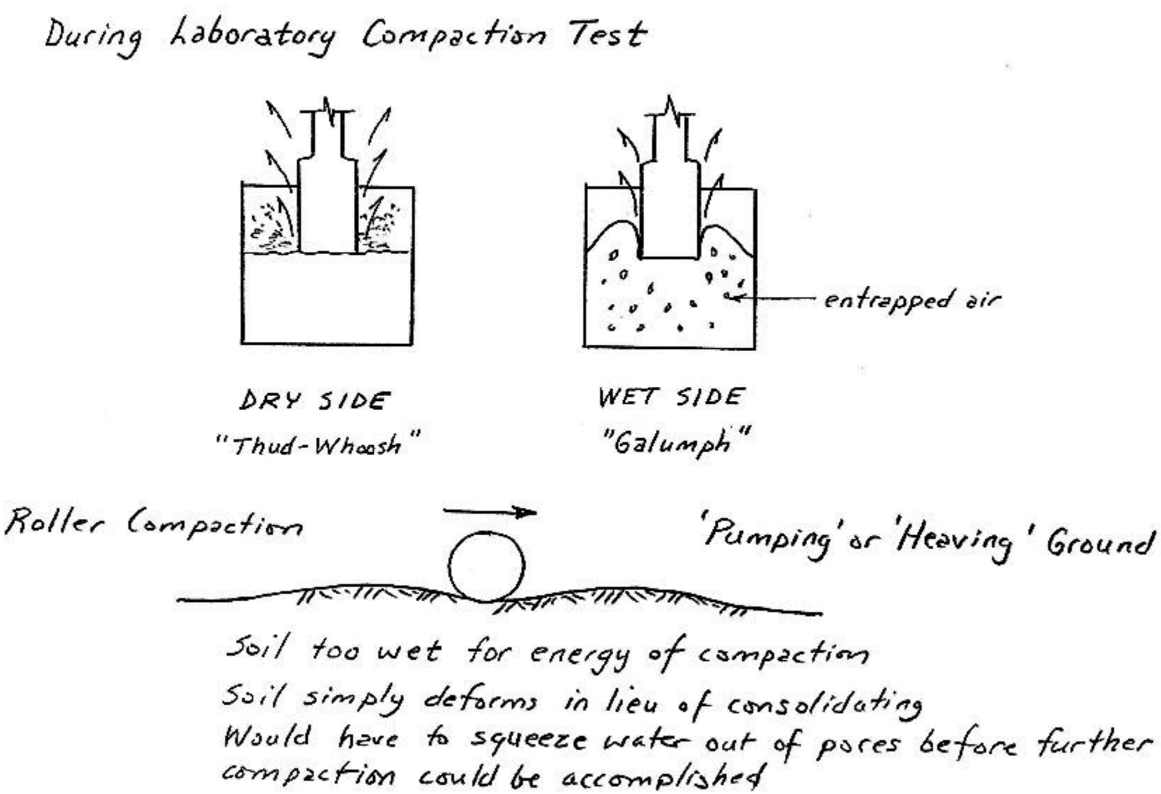
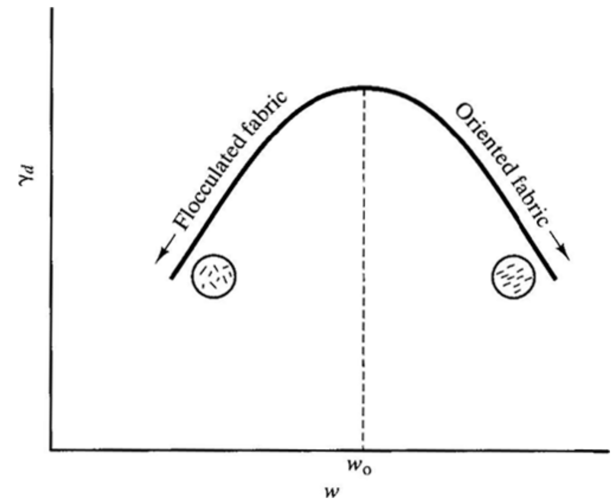
- **The Bouquet Canyon embankments were carefully constructed and monitored over the next 20 years. They ushered in a new era of mechanically compacted embankments. Their 3:1 upstream faces were re-lined with concrete slabs in 1981.**





Soils "dry" of optimum moisture tend to be more flocculated, with a "cardhouse" fabric. Soils compacted "wet" of optimum moisture tend to be more compact, with lower void ratio

- **Sufficient moisture *must be added* to the soil to encourage lubrication of particles for better densification; but it is difficult to expel trapped air from wet cohesive soils, leading to "ground pumping" when vehicles pass over, as sketched above.**

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Standard Proctor "compaction curves"

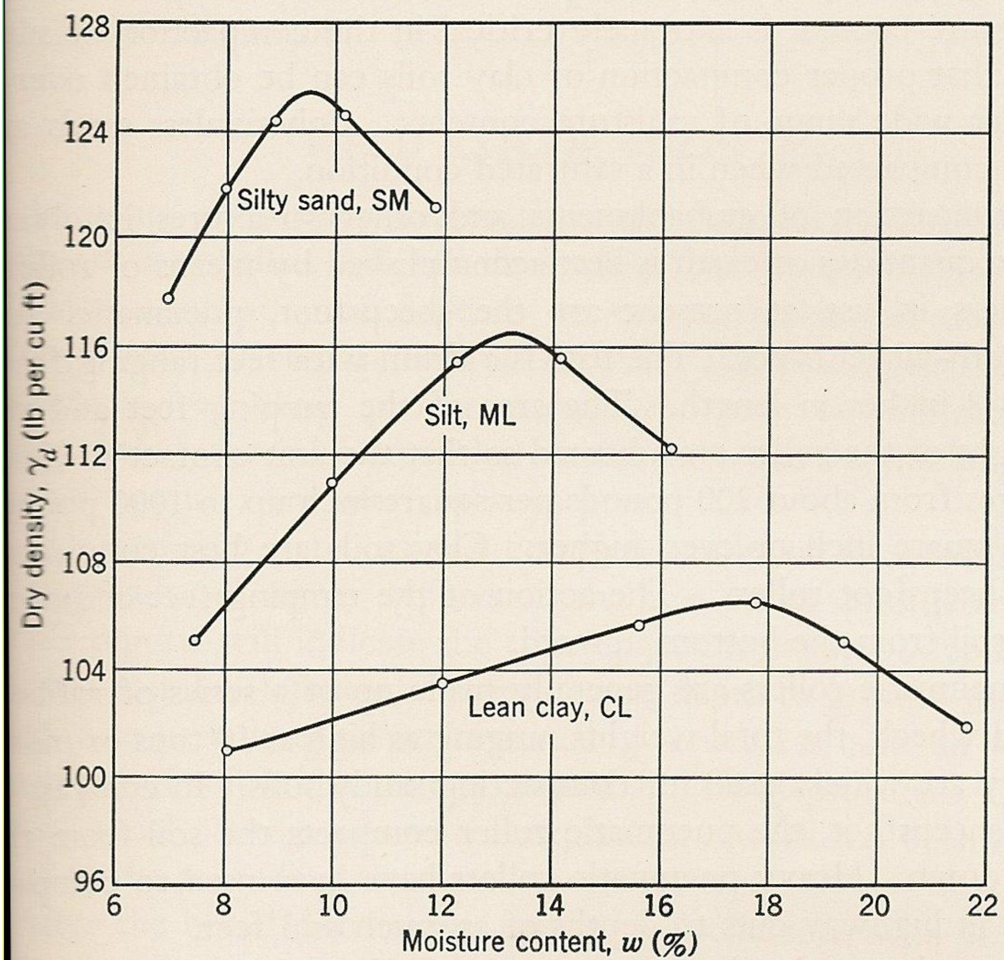
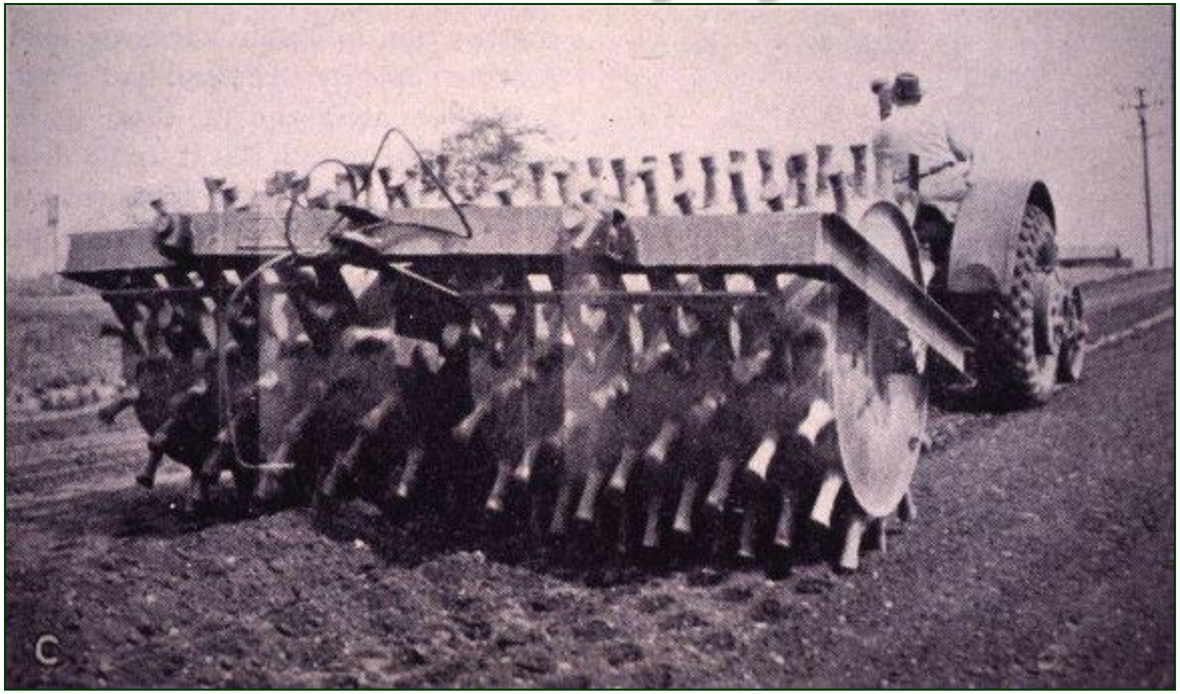


Fig. 171. Standard Proctor compaction curves.

- **Sandy materials typically require the least amount of water (<10%) to achieve good compaction**
- **Silt requires more water than sand; and**
- **Clayey soils generally require the most moisture**
- **These materials are often blended together on actual grading jobs**

Kneeding compaction advantageous for clayey soils



- Between 1904-14 more than 10,000 miles of asphalt highways were constructed in the United States; followed by more than 30,000 miles of concrete paved highways between 1909-25.
- Contractors began building their own variants of spiked sheepsfoot roller to keep up with the expanding industry. Tractors began supplant horse and mule power in the mid-1920s.

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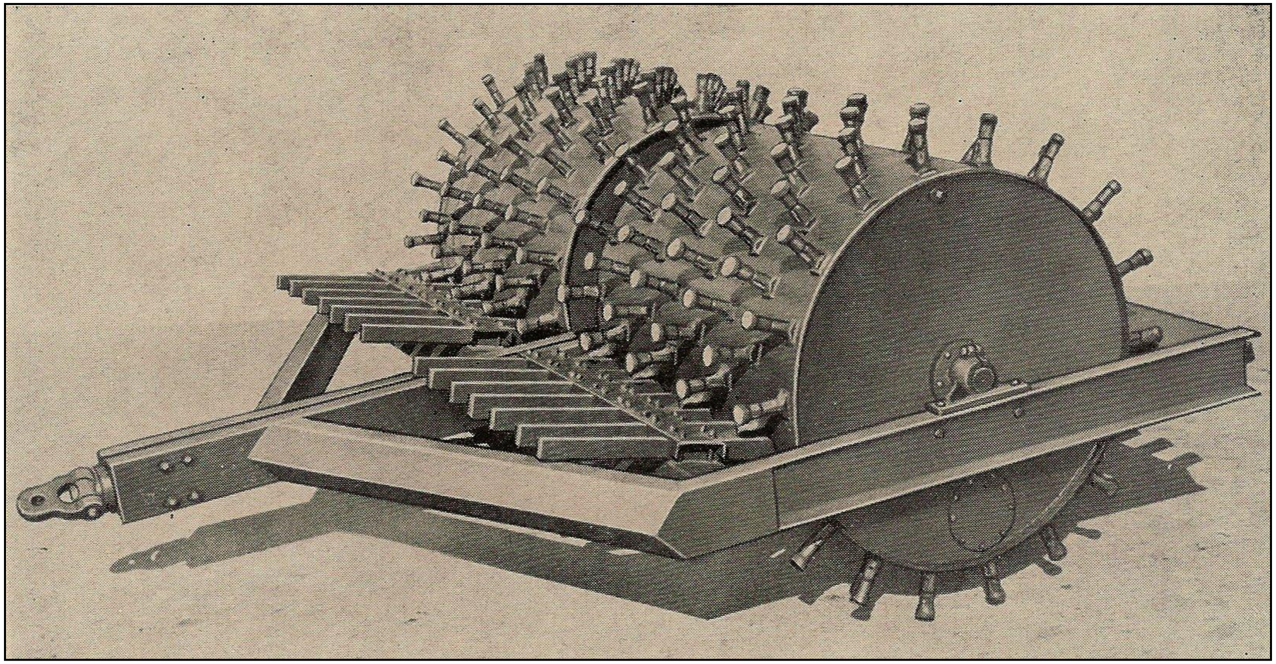
First Roller with cleaning teeth



- In 1931 Euclid Crane & Hoist Co. of Cleveland, Ohio introduced a 12-ton articulated twin-drum tamping rollers, similar to that shown here. By this time manufacturers were pouring about 4000 lbs of molten lead into each drum to increase weight. The drums were 42 inches diameter and 5 ft long.
- This was followed a few years later by the Grace Tamping Roller manufactured in Dallas, Texas (shown above), which was the first sheepsfoot roller equipped with a set of cleaning teeth, designed to remove moist soil that adhered to the spikes.
- Both rollers employed Timkin roller bearings and could be broken down into smaller components for easy transport between job sites (image from the W. E. Grace Co. archives).

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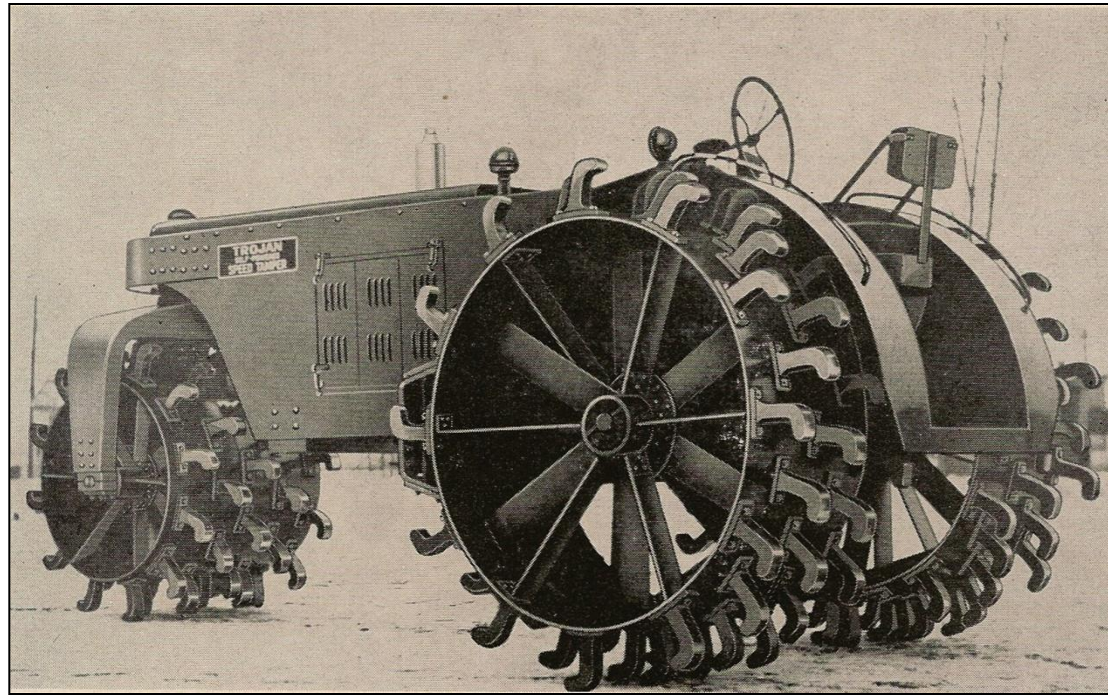
Early self-propelled tamping rollers



- **Right - Ragland's power driven Trojan Self Propelled Speed Tamper roller, produced by Contractor's Machinery Co. of Batavia, NY in the 1930s. It weighed 8,740 lbs and the club headed teeth exerted a 250 psi contact pressure.**
- **Left – In 1925 H.W. Rohl Construction Co. patented a tamping sheepsfoot roller that employed ball shaped heads to heavy wheels mounted on conventional lightweight tractors to use for compacting soils for dams in southern California.**

Rollers designed to break down rock and soil particles

- **Upper left: The grid roller was developed by Gardner Byrne Construction Co of Los Angeles in 1947 to compact soils with a high volume of cobbles or rocky soil mixtures.**
- **The design was acquired by Hyster, who began manufacturing grid rollers in 1949. Note concrete ballast blocks.**
- **Lower Left: The hammerhead Sheepsfoot roller was also developed around 1940 for the same purpose. These remain in production (see below)**

Mike Scullin standing next to a Hyster Grid Roller

Tandem hammerhead Sheepsfoot rollers (above right) being used to compact runway gravel subgrade on Iwo Jima in June 1945

Rapid development of mechanized compaction

- The 1930s and 40s witnessed the rapid development of mechanical compaction of soils, using increasingly larger equipment, often fashioned by contractors. This view shows quadruple 3-ft diameter 5,000 lb rollers, typical of highways work by 1940, just before the Second World War.

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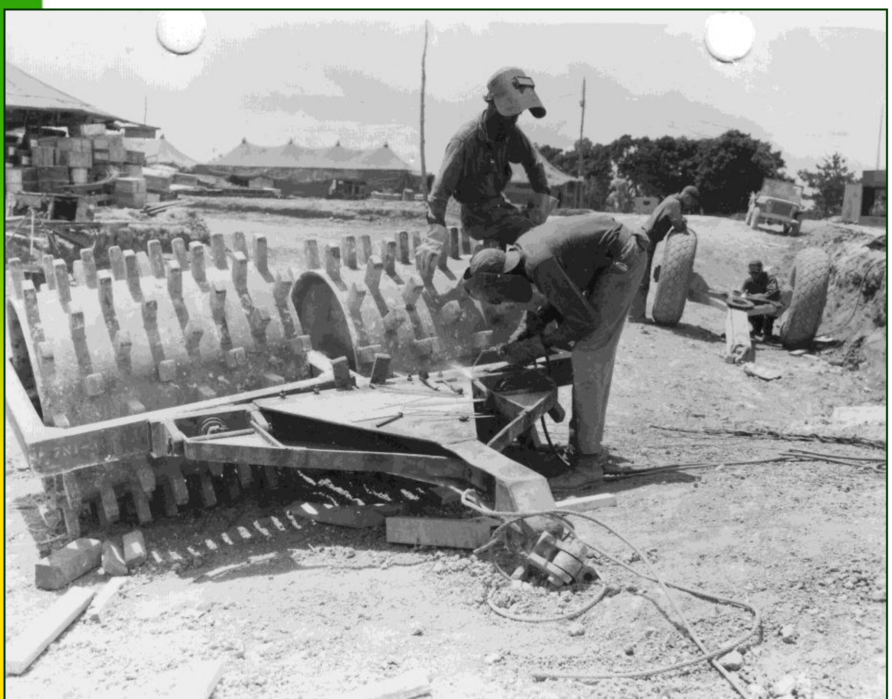
Rectangular spiked sheepsfoot compactors



- During the Second World War (1941-45) square spiked rollers were mass produced because the teeth could be fabricated easily.
- Left above: The tapered tamping spike rollers worked better breaking down brittle coral for Pacific airstrips, and were usually towed in trail, as shown.
- Lower left: After the war many of these smaller 5500 lb dual box spike rollers were sold off as surplus.

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Kneading compaction

- Postwar tests demonstrated the benefit of kneading compaction engendered by spiked sheepsfoot rollers on cohesive soils was verified through lab and field tests.
- This shows sheepsfoot rollers of the Los Angeles Department of Water & Power compacting fill on Eagle Rock Reservoir in 1952.

Big Post-War Rollers

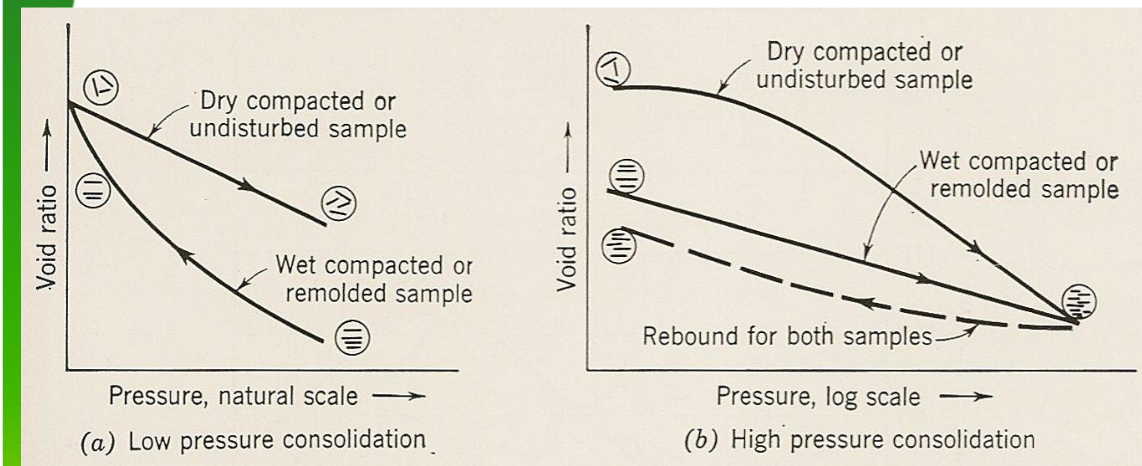
- Upper left: A 5-ft diameter 17.5 ton Letourneau roller is being used on an earth dam embankment in Australia in 1946
- Lower left: A pair of 5-ft diameter sheepsfoot rollers weighed 35 tons, fully loaded. These began to be employed on earth dams in the 1940s, engendering spike pressures of 275 to 375 psi.

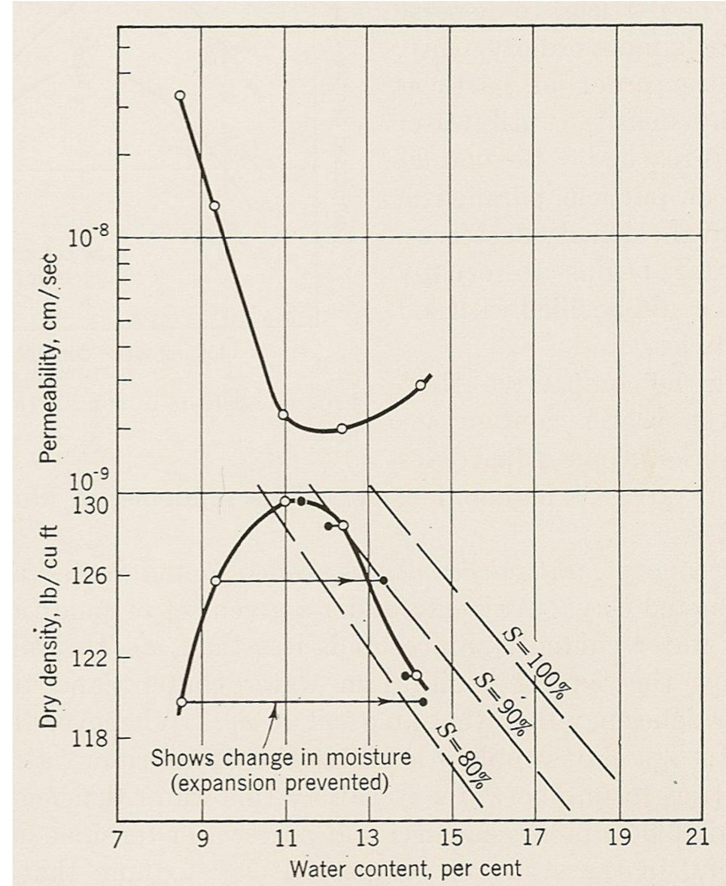
Part 2

WHY DO WE COMPACT SOIL ?

“You don’t always have to do things right, but it sure helps in a pinch” - Jimmy Doolittle

Benefits of Compaction





- **Left: Charts showing the benefits of one-dimensional compression on soil structure, changing from a flocculated (open) to more dispersed (layered) structure**
- **Right: Impact of compaction on permeability of Siburua clay, illustrating the dramatic decrease in permeability with increasing density and water content. Both charts from T.W. Lambe, in Leonards' *Foundation Engineering* (1962)**

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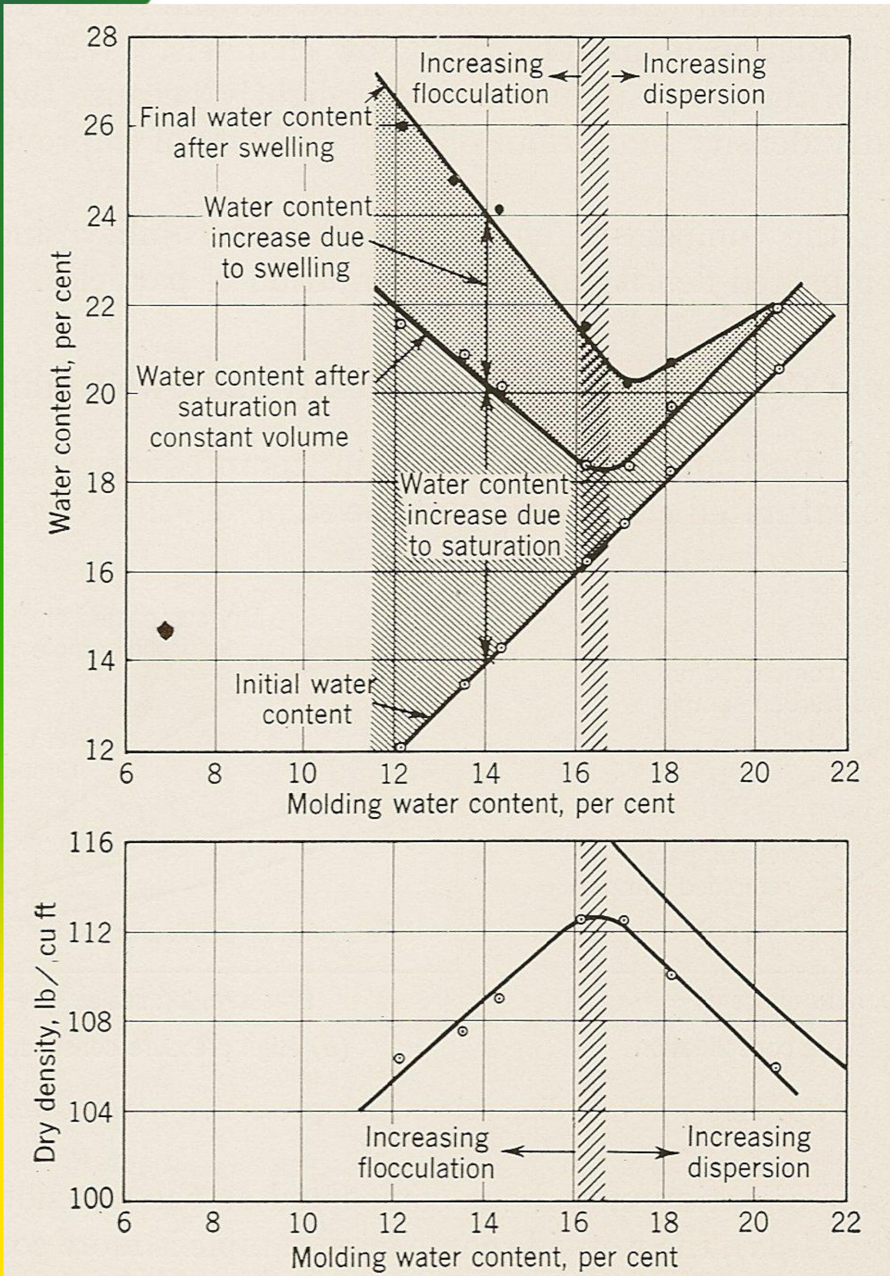

Benefits of compaction

- Influence of **molding water content** and **soil structure** on swelling characteristics of sandy clay, from Seed and Chan (1959).
- Note significant increase in water content on the "dry" side of the compaction curve
- This is why it is so important to moisture condition expensive soils "wet" of optimum moisture content

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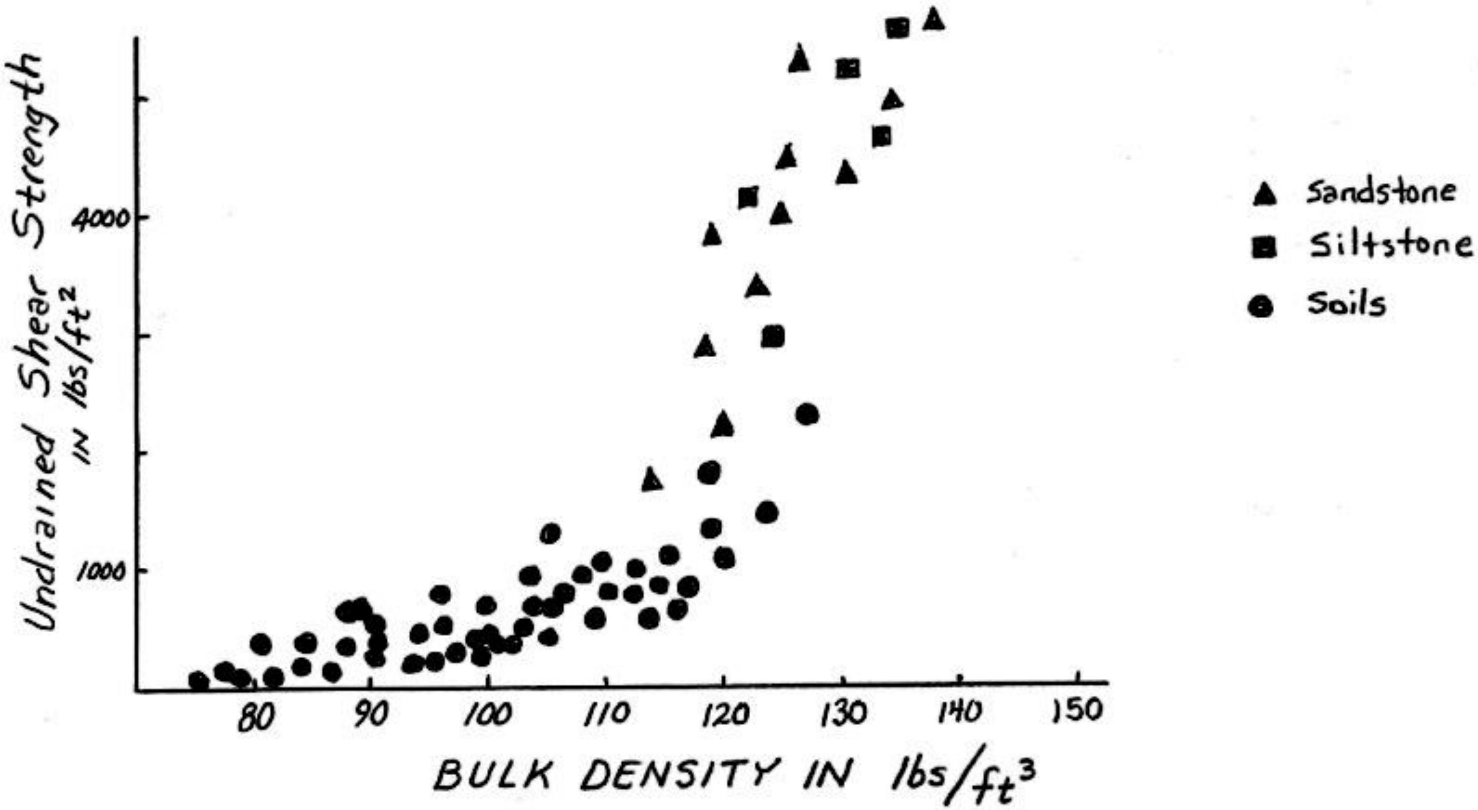

- **We also compact soil and rock mixtures to *increase* their effective shear strength, making them more able to resist gross deformations**

FILL PRISMS

- **We compact soils to reduce the long-term settlement. Fill prisms reach their greatest dimensions over old watercourses, like the one shown here. Excessive settlement may eventually lead to complete slope failure (note scarp)**

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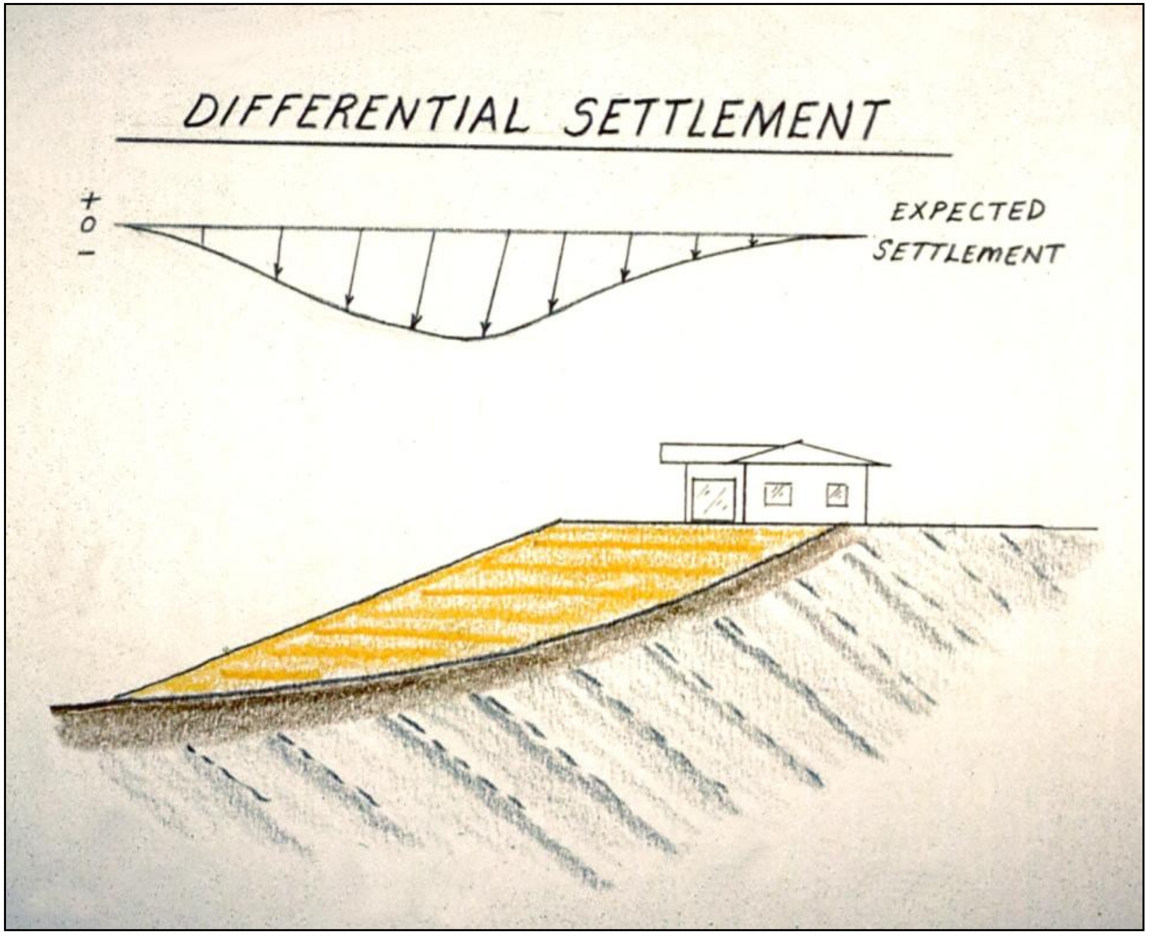
DIFFERENTIAL FILL THICKNESS



- **We compact soil to reduce differential settlement. Sidehill embankments are of differing thickness, which promotes differential settlement and differential heave**

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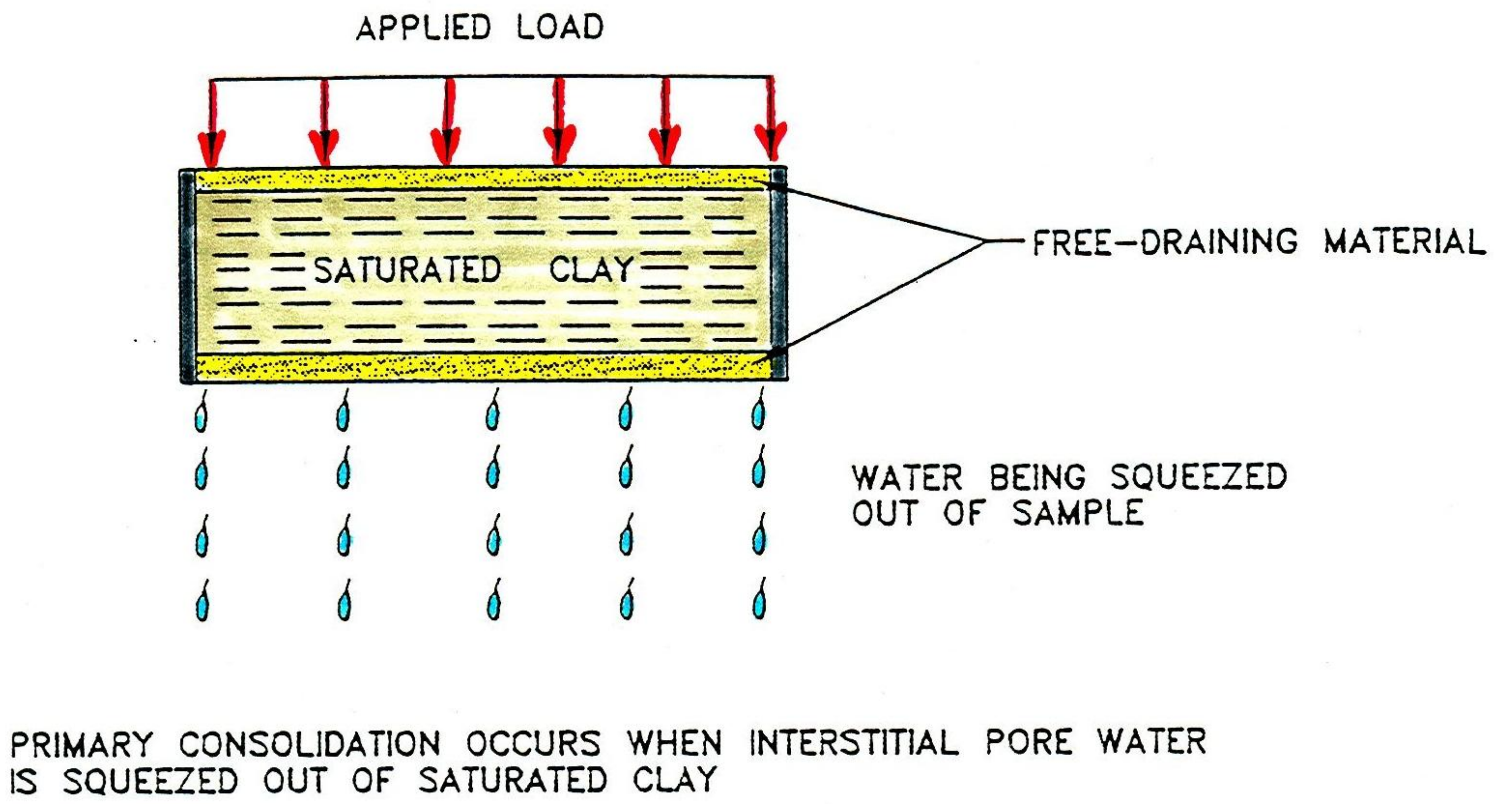
SLOPE CREEP AND DILATION

- **We compact (densify) fine grained soils so they absorb less free moisture. Soil tends to absorb moisture with time and softens, promoting bearing capacity failures, settlement, loss of strength and slope creep, evidenced here by linear tension cracks in the pavement.**

PRIMARY CONSOLIDATION



- **Primary consolidation occurs when water is expelled from the pore spaces of a saturated soil. It is not usually a problem in compacted clayey embankments less than 15 to 20 feet deep.**

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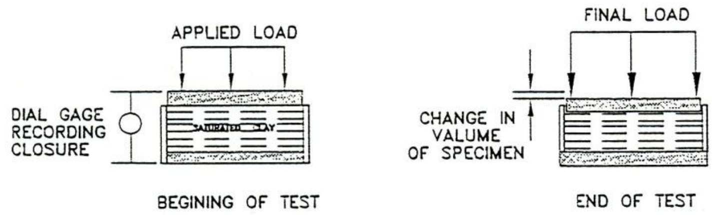
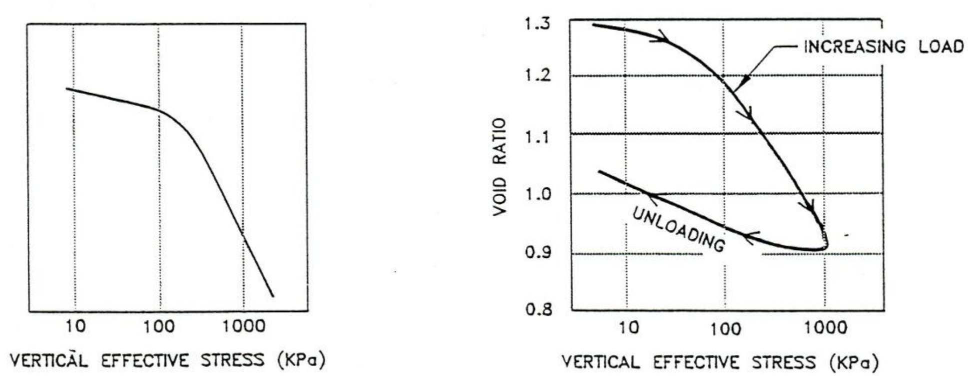
1-D CONSOLIDATION



CHANGE IN SOIL VOLUME MEASURED IN ONE DIMENISONAL CONSOLIDATION TESTS



TRADITIONAL REPRESENTATIONS OF PRIMARY CONSOLIDATION TESTING.

- **Estimates of consolidation-induced settlement rely upon data derived from one dimensional odometer tests, like that sketched here.**

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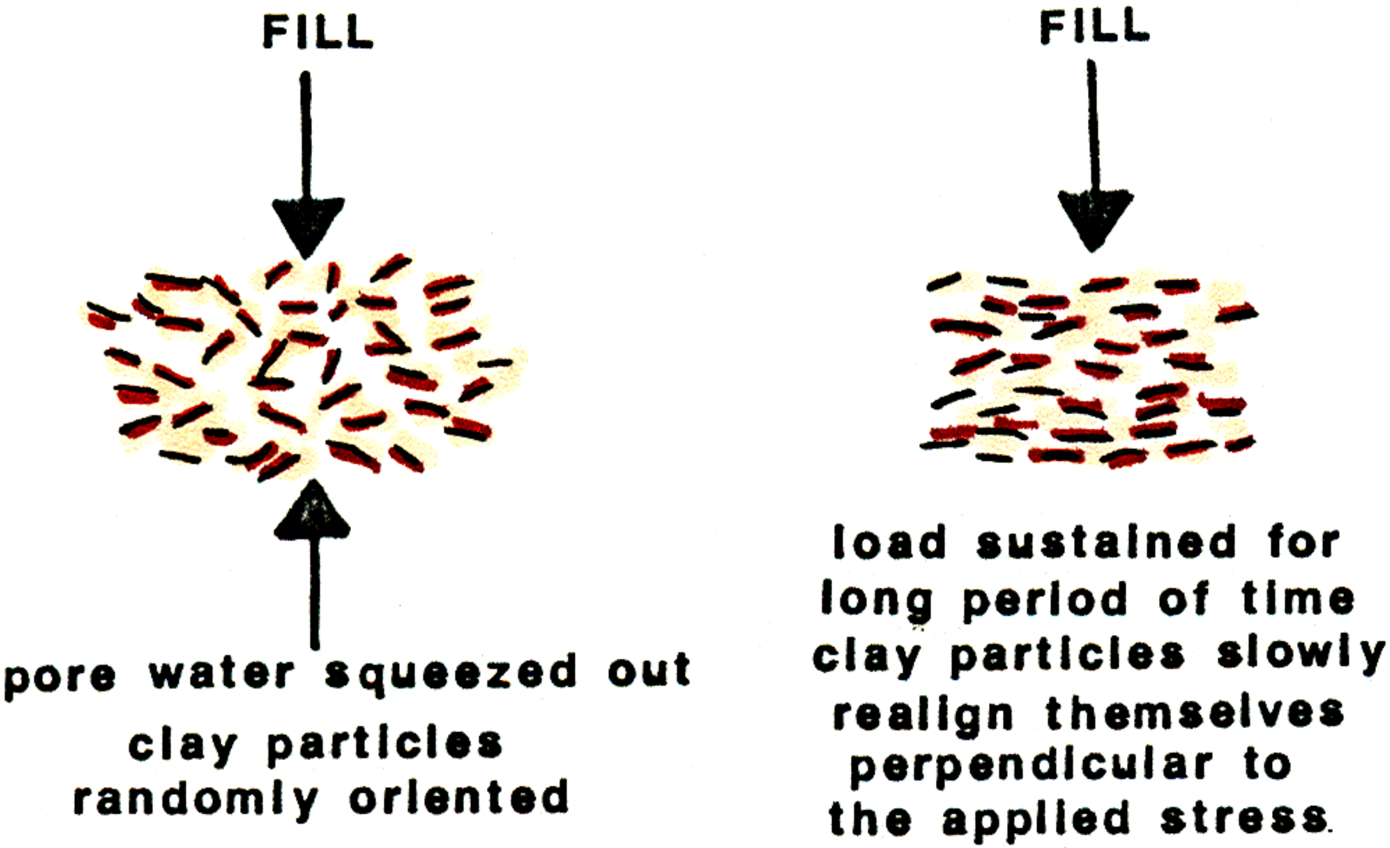
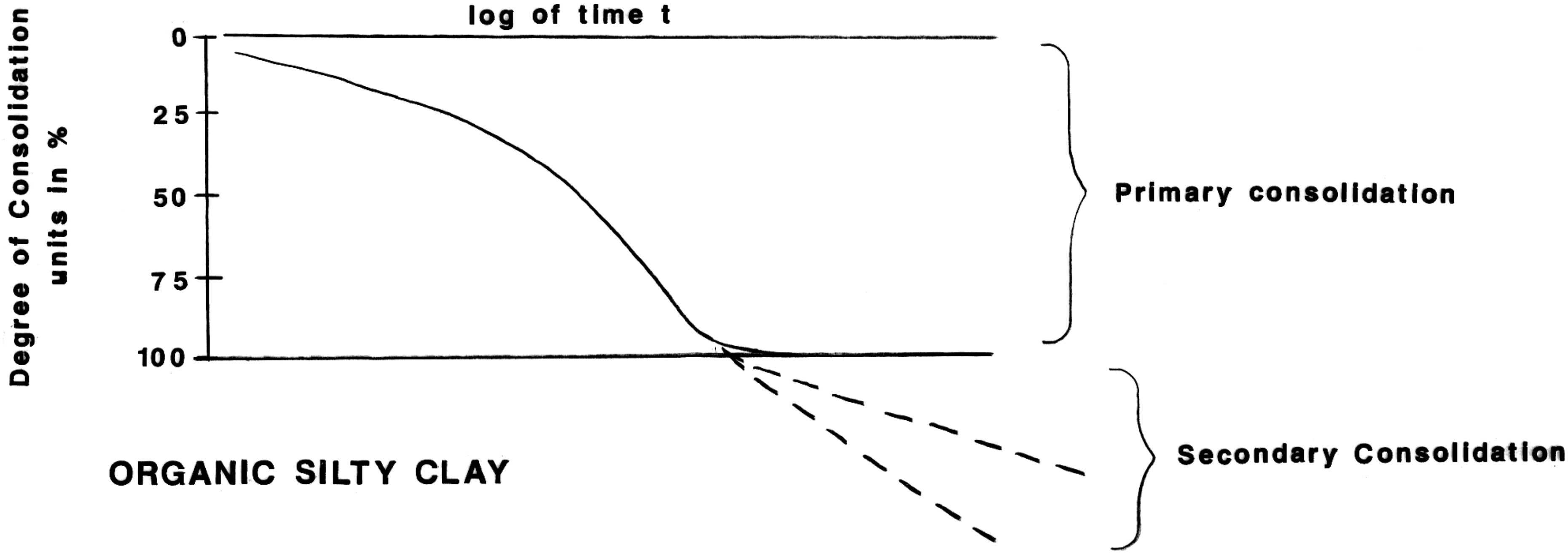
SECONDARY CONSOLIDATION



- **Secondary consolidation occurs indefinitely as clay platelets re-align themselves under sustained loading and pore water is expelled. Usually occurs in underconsolidated estuarine and lacustrine clays.**



- The time required for consolidation to occur depends on the imposed load (surcharge), the thickness of the compressible strata, and the length of the pore water drainage path(s).
- Primary consolidation ceases after a predictable period, but secondary consolidation may continue at a near-constant rate, for a much longer period of time.

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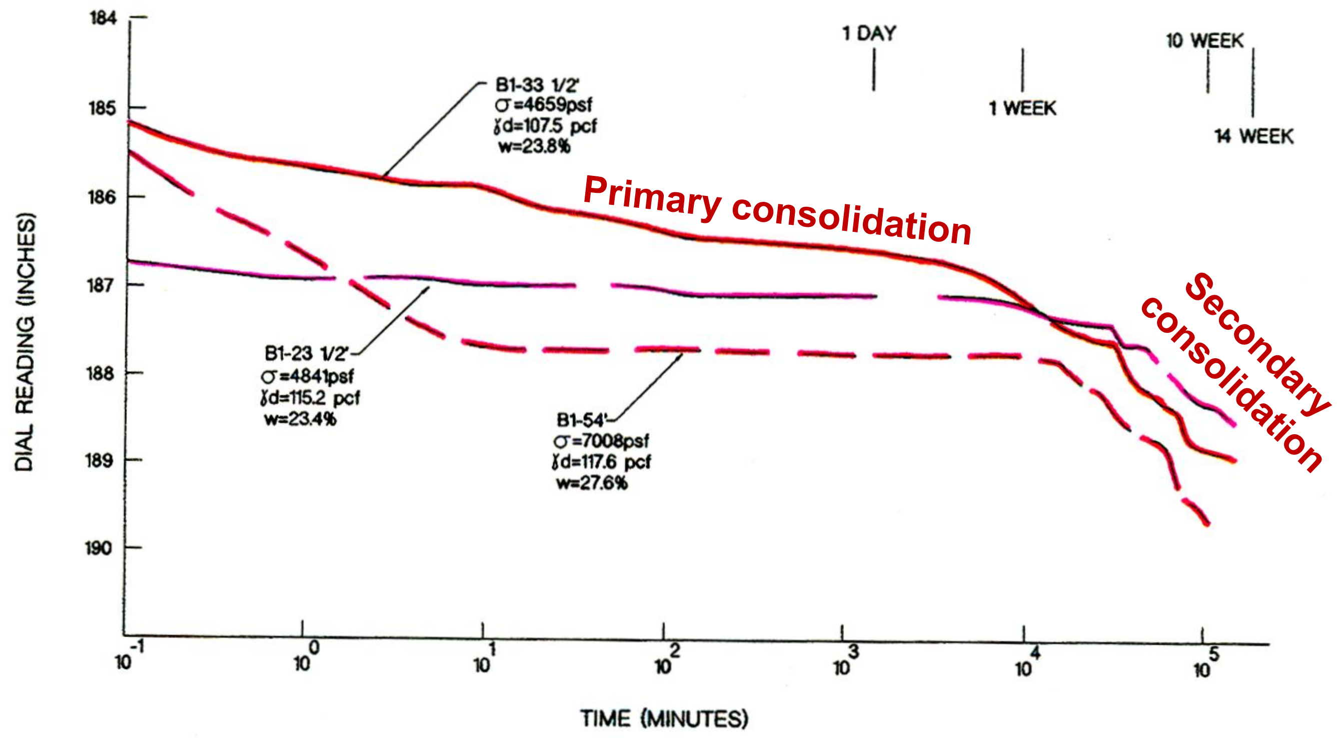

- **Lab compression data from an urban fill placed in 1963 and sampled in 1985, from depths between 24 and 54 feet. Secondary consolidation was not evidenced in the consolidation apparatus until after a week. These one-dimensional consolidation tests were continued for 14 weeks (from Rogers, 1992).**

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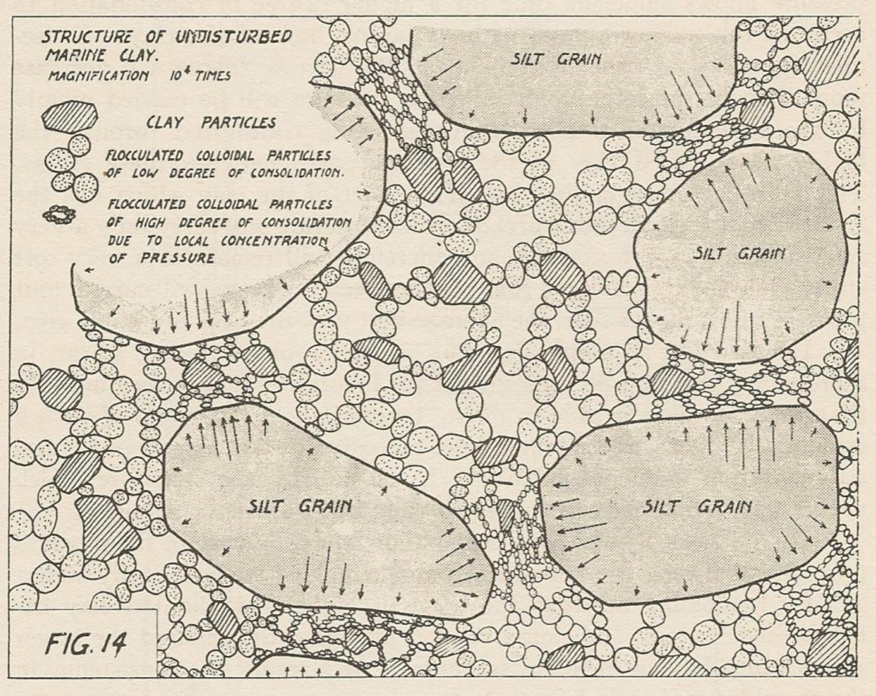
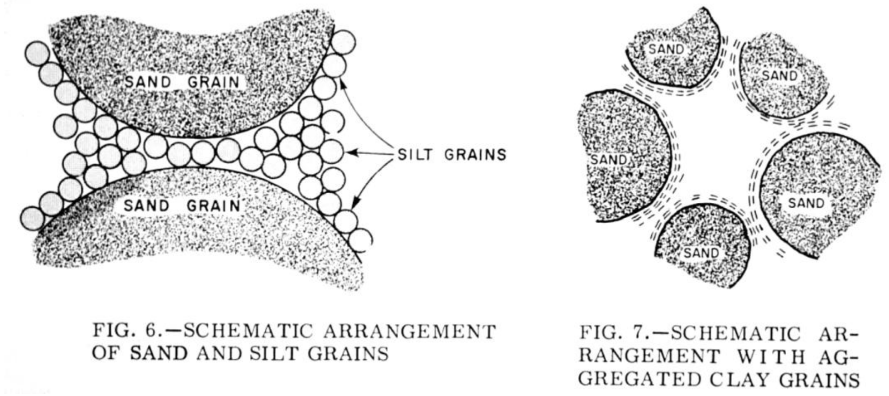
HYDROCOMPRESSION





Honeycomb structure of a clay-silt sediment

Honeycomb structure of a silty sand

- **Hydrocompression occurs water is added to mixtures of silt, silty sand or aeolian silts and sands, which have not previously been saturated under sustained load. The figure at upper left is taken from an article by Arthur Casagrande in the *Journal of the Boston Society of Civil Engineers* in April 1932.**

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Hydrocompaction of low density sands and silts

Dr. Jack W. Hilf (1912-92)

Jack W. Hilf, Ph.D., PE led a group of engineers at the US Bureau of Reclamation that performed pioneering research on low relative density and susceptibility to hydrocompression, while working on Trenton Dam project in Nebraska.

- **The Bureau of Reclamation constructed a series of distribution canals like the Meeker-Driftwood Canal in the Republican River Valley of Nebraska, shown above left. These were founded on low density loess and blow sands that were susceptible to densification by seepage from the canals.**
- **Engineering geologists with the California Department of Water Resources made similar discoveries a few years later in the Kern and Tulare Basins (lower left), while working on the State Water Project canal.**

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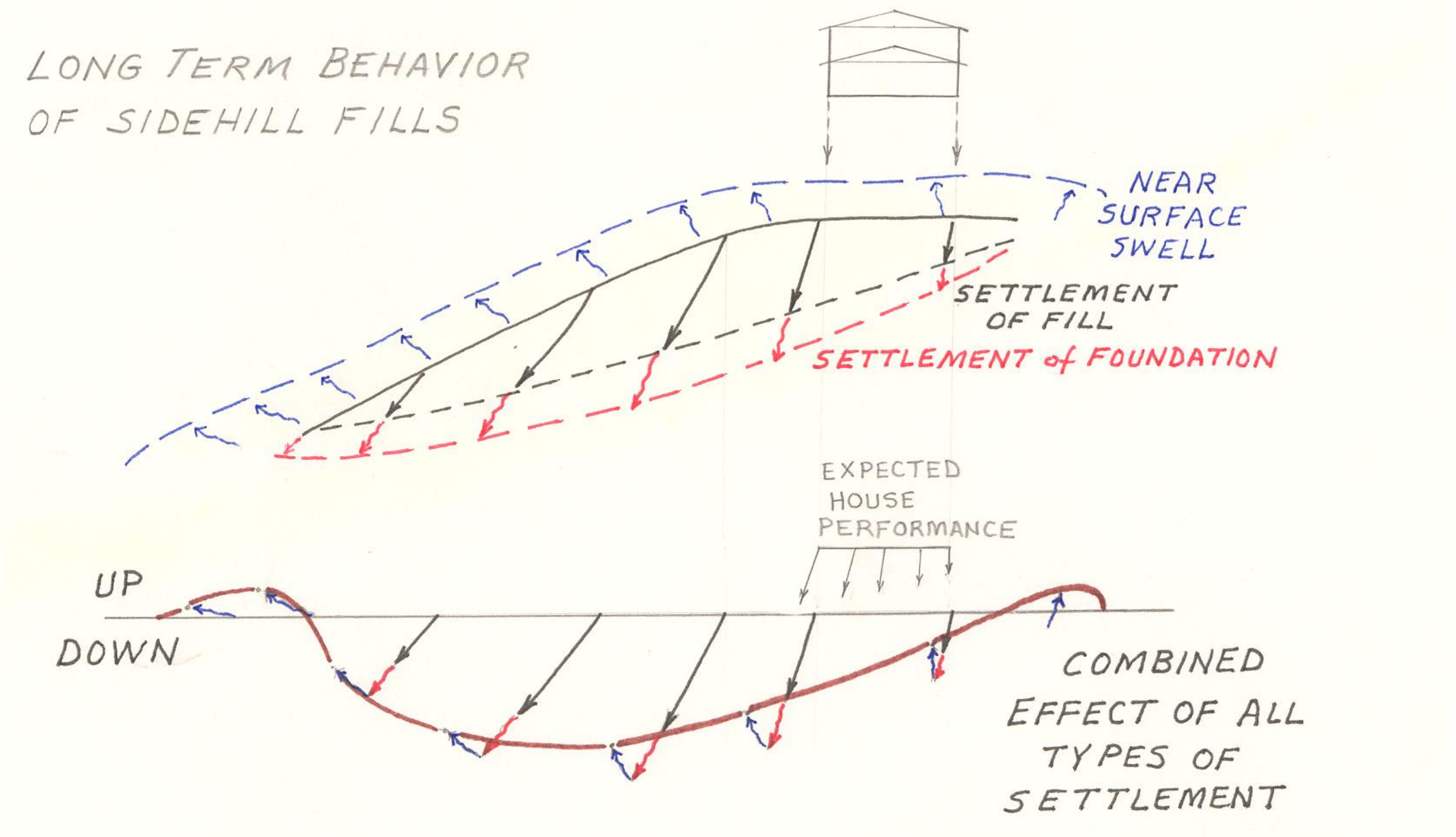
LONG TERM BEHAVIOR



- **Long term behavior is usually influenced by the aggregate sum of settlement, heave and creep of fill and underlying foundation materials**

- Another form of hydrocompression is loosley termed **"clod consolidation."** This is actually a mechanism of ***soil collapse*** frequently caused by percolation of free water (in this case, through a gunite pool shell) into low density fill of low water content.
- This view shows typical settlement of concrete flatwork placed near the crest of a modest embankment. The loose-dumped muck from the pool excavation has settled about 6.5 inches (seen at far right).

Part 3

COMPACTION TESTS

evolved to support bomber loads on runways

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Grass runways and parking areas were common prior to 1940 because most aircraft were of relatively light weight

The Boeing XB-15 bomber at Wright Field near Dayton, Ohio in 1937

Need to increase bearing capacity

- Up through the mid-1930s military aircraft were relatively light, and could be supported on natural fields with grass runways, like that shown at upper left
- In 1937 the Army Air Corps began flight testing new long range bombers, like the Boeing XB-15, at lower left.
- This aircraft had a gross takeoff weight of 71,000 lbs, spread on tandem main gear tires and a single tail wheel. It could only use select concrete runways.
- Prior to this time, 12,500 lbs were the heaviest wheel loads any runway had been designed to handle

The airfield runway crisis of 1941

- The massive **Douglas B-19 bomber** had a wingspan of 212 feet with a maximum gross weight of 162,000 lbs, spread onto just three tires. Its extreme weight engendered bearing failure of the concrete ramp at the Douglas factory in Santa Monica, forcing delays until a thicker concrete runway could be constructed.
- On June 27, 1941 the B-19 departed Clover Field in Santa Monica and landed at March Field near Riverside, California. Upon touchdown and taxi its massive 8-foot diameter tires inflicted noticeable damage to the taxiways and parking apron. This damage hastened an investigation by the Army Corps of Engineers, eventually leading to development of new design procedures to enhance compaction of pavement subgrades, which became the **Modified Proctor Compaction Test.**

Most bearing capacity failures occurred on taxiways in the European Theater

During World War II, the Corps of Engineers noted an increasing problem with pavement distress near the edges of heavily traveled taxiways. The weak link appeared to be subgrade preparation (images from 401st Bomb Group at Deenethorpe, UK)

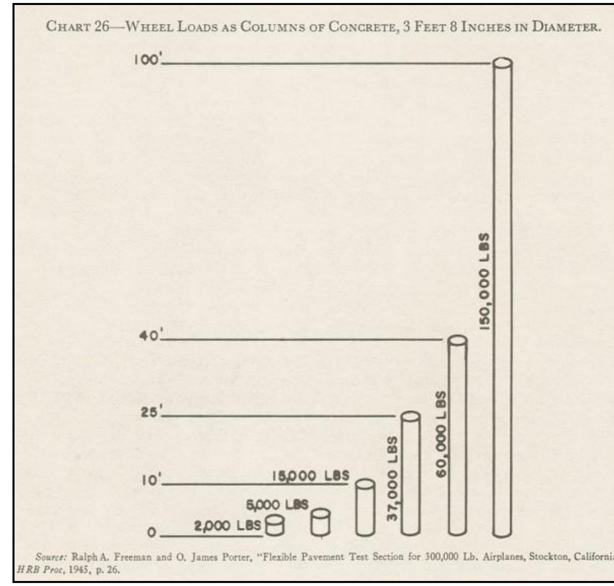
The Corps of Engineers
Airfield Pavement Design Advisory Council
at the Stockton Test Track in California in 1944

Army Corps of Engineers Airfield Pavement Design Advisory Council, standing on a B-19 bomber tire at the Stockton Test Track

Front row (left to right): Colonel Henry C. Wolfe (who had worked on the Fort Peck Dam soil mechanics problems), Prof. H.M. Westergaard of Harvard, and Dr. Philip C. Rutledge of Moran, Proctor, Freeman & Meuser. Back row, left to right: Prof. Arthur Casagrande of Harvard, Thomas A. Middlebrooks (the Corps senior expert in soil mechanics, who had also worked on the Fort Peck Dam landslide), James L. Land of the Alabama State Highway Department, and O. James Porter of the California Division of Highways, who originated the CBR test procedure, beginning in 1928.

Stockton Airfield Test Track

240,000 lb pneumatic roller used in the runway pavement tests at the Stockton Airfield test track



Aircraft wheel loads depicted as equivalent columns of concrete, three feet in diameter (from Freeman and Porter, 1945)

- **Stockton Airfield was the Corps' principal test site for evaluating Pappy Porter's California Bearing Ratio (CBR) test to compare subgrade modulus with various wheel loads and repetitions, working with the California Division of Highways and the Sacramento District of the Corps of Engineers under the supervision of Porter, between 1942-45.**

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- In 1945 the Army Corps of Engineers conducted numerous experiments with modified rollers, such as the railroad rail spike roller shown here. It engendered spike pressures of 260 psi empty, and up to 1080 psi when the roller was loaded with slurry, the case shown here.
- These were designed to evaluate rollers exerting 250, 450, and 750 psi; a 19,500-pound wobble-wheel roller; and 10,000-, 20,000-, and 40,000-pound rubber-tired wheel loads (simulating increasingly heavy bombers).

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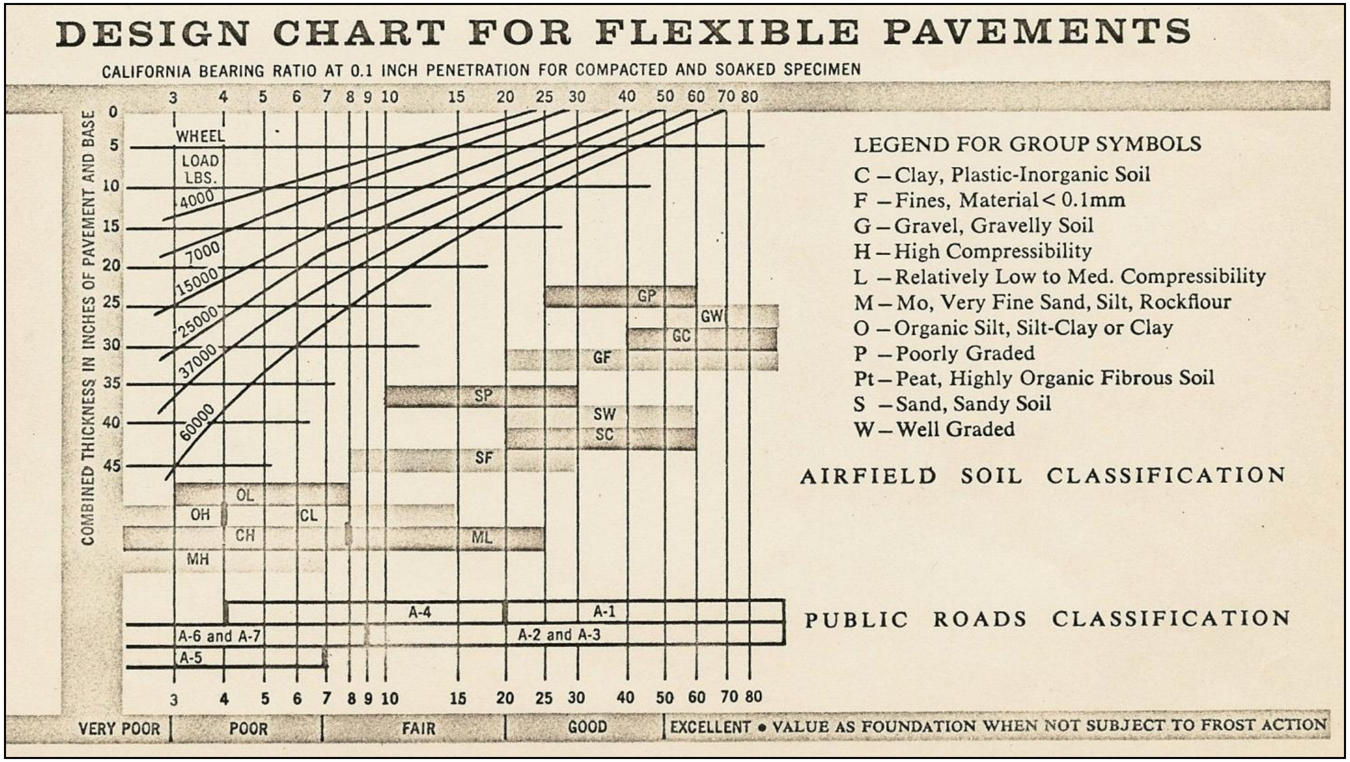
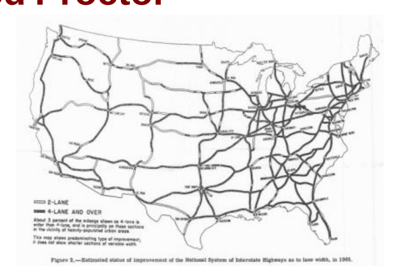
The Corps of Engineers developed flexible pavement design procedures



■ During the Second World War (1941-45) the Army Corps of Engineers developed specialized design procedures for flexible asphalt runways that incorporated the properties of the pavement subgrade, because the aircraft wheel loads are transmitted directly to the subgrade in flexible pavements. This focused attention on the importance of ***subgrade compaction***, leading to the **Modified Proctor compaction test** in 1946.

■ These same design procedures were subsequently incorporated into post-war design of flexible asphalt highway pavements (as shown in the above chart), which Were used in the **Interstate & Defense Highway Program**, beginning in 1955.



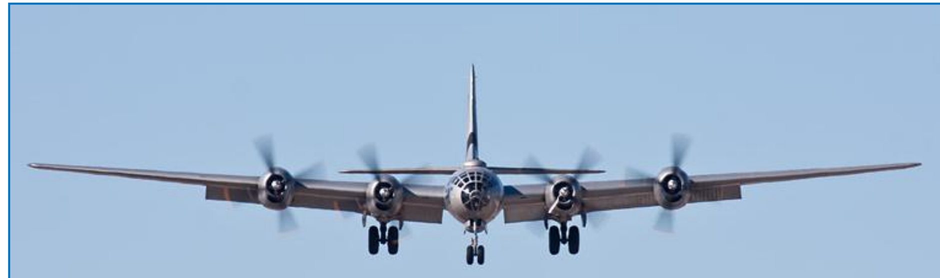
Flexible Asphalt/Concrete and bituminous pavements

- **Simplified flexible pavement design methods had an enormous impact on highway and airfield construction during the Second World War, leading to a post-war explosion in highway construction, beginning with the first Federal Aid to Secondary (FAS) highways program in 1944.**

The Big Bomber

- With a maximum takeoff weight of 133,500 lbs, the **B-29 Superfortress** bomber required new pavement design methods and construction techniques at western Pacific bases
- In the fall of 1944 ‘Pappy’ Porter was dispatched to the Mariana Islands to troubleshoot the pavement problems

B-29s queuing up on a taxiway at North Field, Tinian

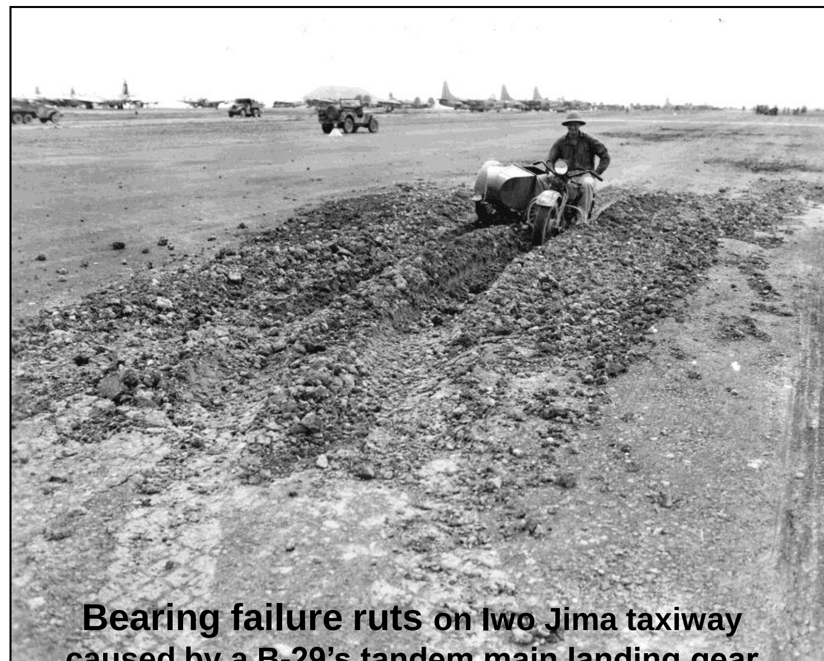


The landing gear of the B-29 spread 133,500 lbs on six tires

Bearing failures
B-29s in Pacific Theater

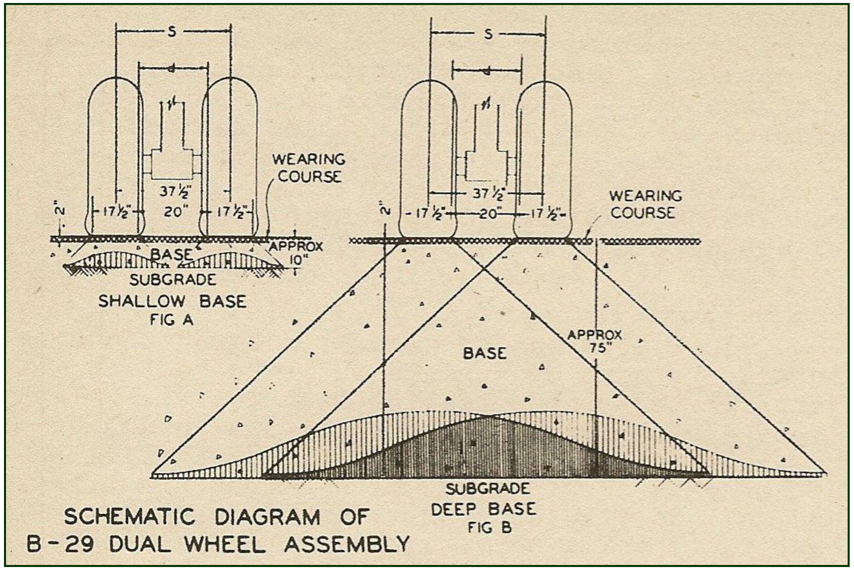
These images show B-29 bombers on taxiways in the Mariana Islands and Iwo Jima, where an unusually high degree of pavement distress occurred because of inadequate subgrade compaction. The volcanic cinders at Iwo Jima proved particularly problematic, as shown below.

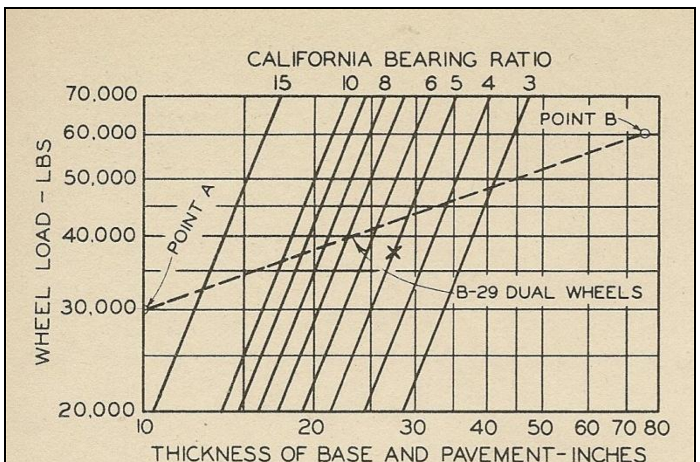
Transient aircraft ramp at Iwo Jima, where bearing failures occurred, despite fact it was founded on 36 inches of volcanic cinder rock



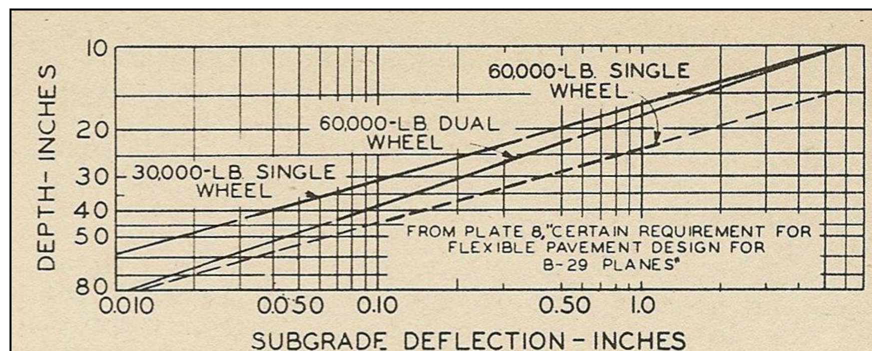
Bearing failure ruts on Iwo Jima taxiway caused by a B-29's tandem main landing gear

Solving the B-29 pavement design problem – focusing on subgrade compaction





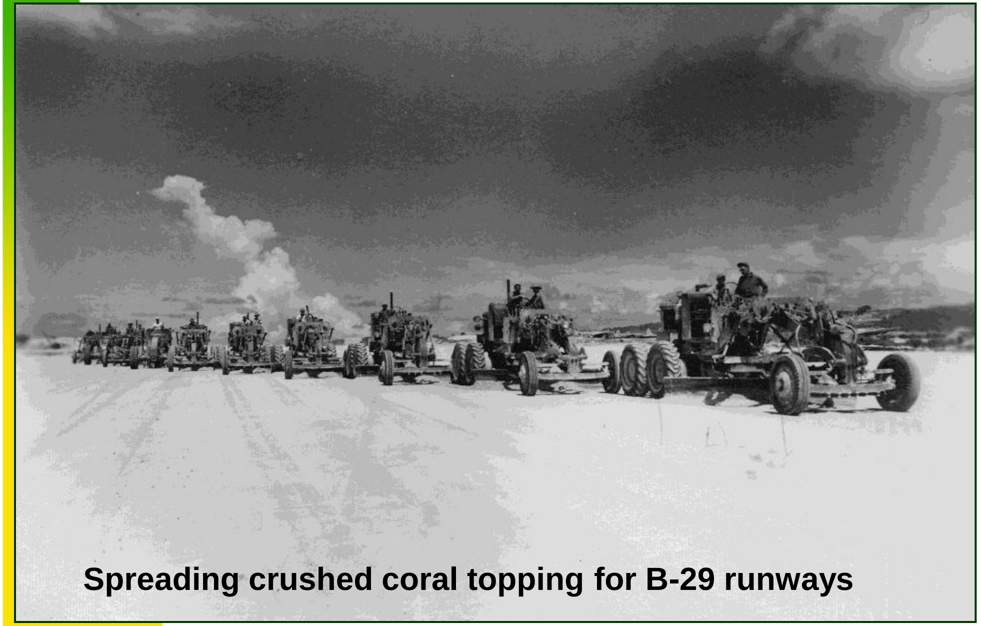
DEVELOPMENT OF DESIGN CURVES-60,000 LB LOAD ON B-29 DUAL WHEELS



SUBGRADE DEFLECTIONS SINGLE VS DUAL WHEELS

Short hauls from quarry to placement on Iwo Jima

Compacting gravel subgrade for runways



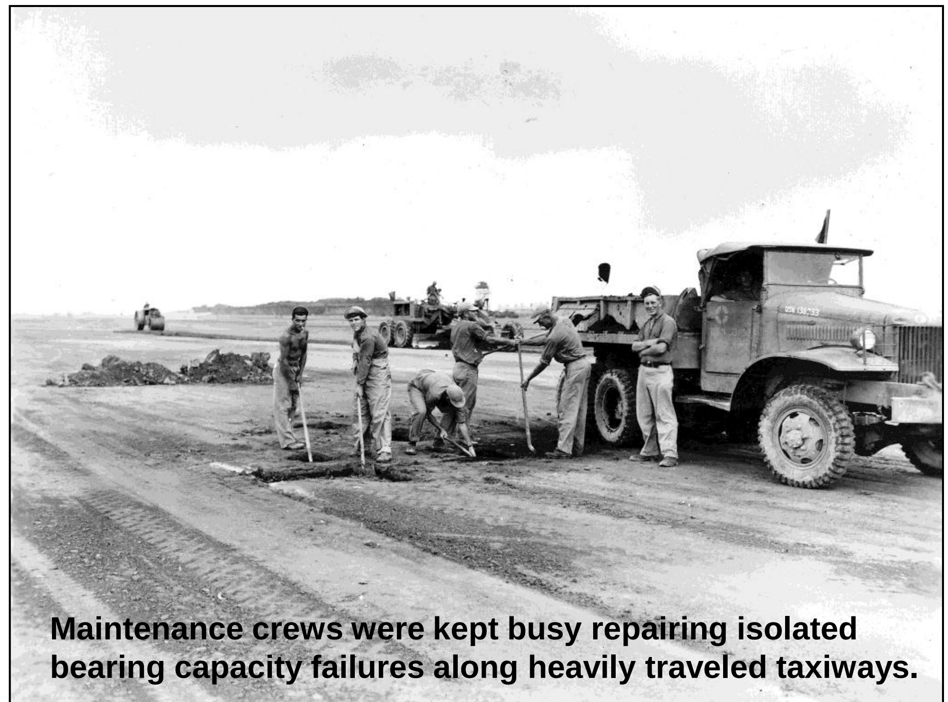
Spreading crushed coral topping for B-29 runways

Rolling crush coral pavement for B-29 runways

Laying and spreading 30-inch thick crushed coral topping layer in August 1945 at Yonton Field on Okinawa

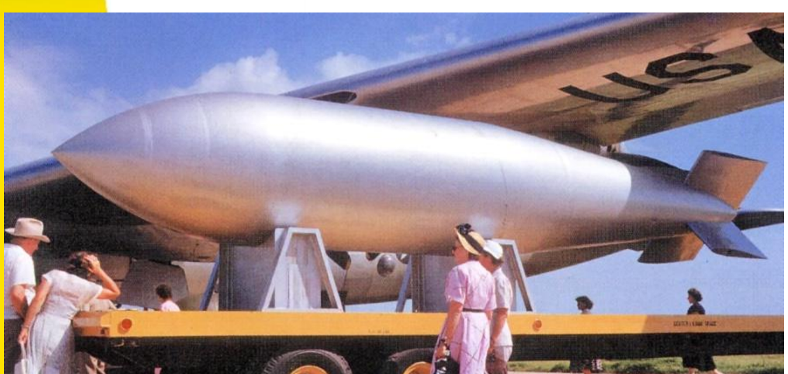
By the war's end in August 1945, Yonton Field on Okinawa was being constructed with a well-graded mix of crushed coral 30 inches thick!

54-inch thick B-29 harsdstand at North Field on Tinian

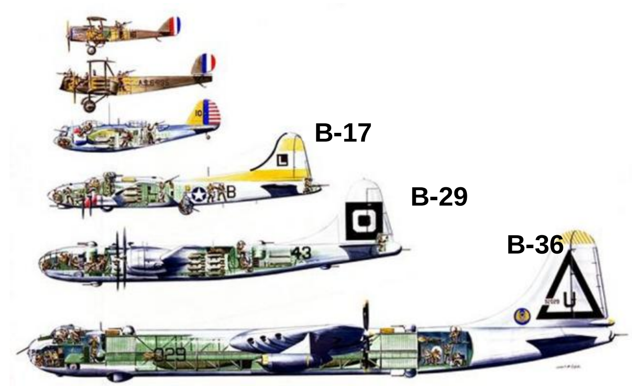


Maintenance crews were kept busy repairing isolated bearing capacity failures along heavily traveled taxiways.

After the Second World War, the bombers kept getting larger



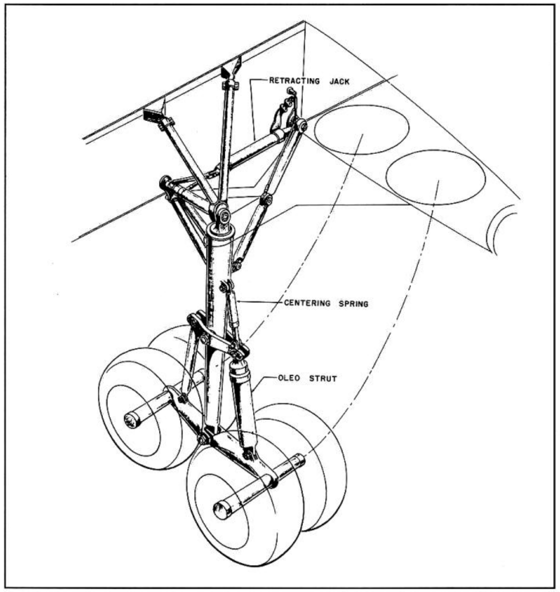
In 1952 the 10.4-megaton Ivy Mike hydrogen bomb was introduced, shown at left. It weighed 42,000 lbs, and the B-36 was the only aircraft that could carry it. This created another runway crisis…

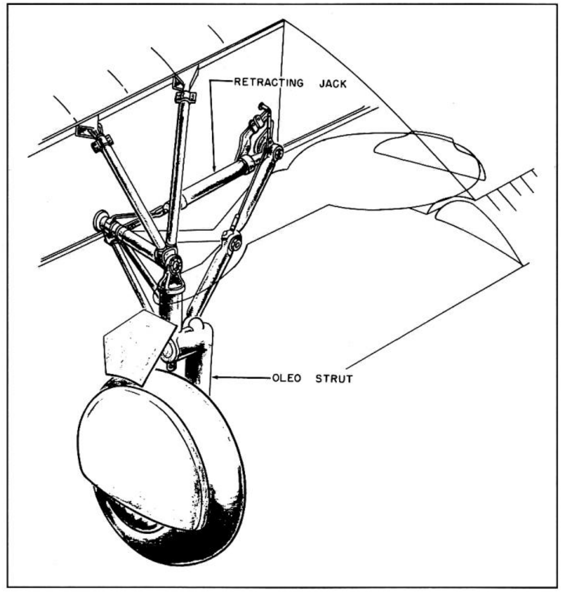


Air Force officers looking over one of the 110-inch diameter tires of the YB-36

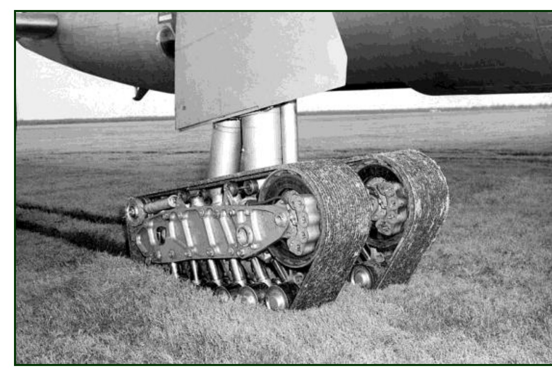
- **The massive 110-inch diameter wheels of the prototype Convair YB-36 bomber became the largest post-war pavement design problem, requiring pavement sections of 18 to 50 inches thickness, originally developed for the B-19. These subgrade materials were compacted to the new Modified Proctor standard**.

4-tire undercarriage bogie landing gear





- **One aspect of the solution was to replace the massive 110-inch tires with a set of four 56-inch tires set in pair of 4-wheel undercarriage bogie landing gear; common to all heavy aircraft today**



An unusual tracked landing gear configuration was among the many possibilities that were tested

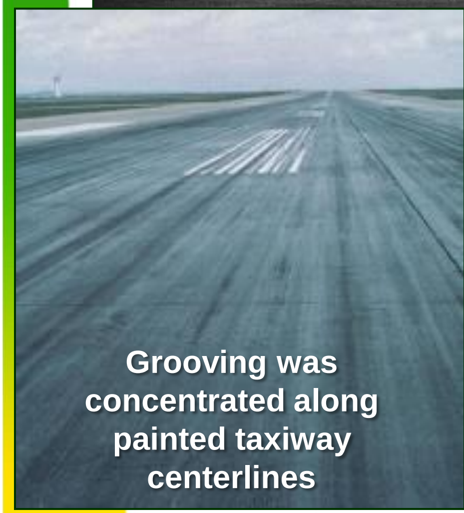
The Modified Proctor Compaction Test (1946)

The Modifed Proctor Test uses a 10-lb hammer in an 18-inch drop sleeve. Both the original and Modified Proctor test components are shown here

- The "modified Proctor basis" of 1946 was developed by the US Army Corps of Engineers Waterways Experiment Station in Vicksburg.
- It uses the same cylindrical mold as the Standard proctors (4 in. dia and 4.6 in. high, with a removable mold collar 2.5 in. high). The mold volume is 1/30th cubic foot
- A 10 pound hammer, 2 inches in diameter, was pulled upward and allowed to free-fall 18 inches, onto the soil (15 ft-lbs per blow)
- The soil was compacted in five lifts, with an average thickness of 0.80 inches/lift.

- 25 blows were exerted per lift, which equals 25 x 15 = 375 ft-lbs. The total input energy for the five lifts is 5 x 375 = 1875 ft-lbs on a soil sample with a volume of 1/30th cubic foot. This equals 56,250 ft-lbs of compactive energy per cubic foot of soil
- It was designated ASTM Test D1557 or Modified AASHTO T180, initially adopted in 1958

Pavement grooving along taxiway center lines because of concentrated wheel loads



Grooving was concentrated along painted taxiway centerlines

In 1955 a number of flexible pavement airfields supporting B-47 Stratojet bombers (shown here) were causing "grooving" of their taxiways along their painted center lines. Corps of Engineers researchers noted that the B-47 used a bicycle landing gear that applied two gear passes each time the plane taxied over the pavement. The practice of painting taxi-stripes for pilots to follow down the center of lanes narrowed the lateral wander of the bombers and concentrated wheel loads over very small areas.

- In 1954 WES-Vicksburg began a full-scale study of channelization, ultimately collecting data from twenty-three Air Force bases with 116 bituminous-surfaced facilities. B-47 load repetitions were also applied 6X that assumed in runway design because the plane enjoyed higher utilization than previous piston-engine aircraft.

Willard J. "Bill" Turnbull, PE (1903-97) received his BSCE from Nebraska in 1925 and became Chief Engineer of the Soils Division at the Waterways Experiment Station of the Corps of Engineers in 1941, where he played a major role in developing standards of practice for soil compaction and flexible pavement design over the succeeding decades, retiring in 1969.

Pavement Tests

- In 1955 the Corps of Engineers built this 258,000 lb roller to simulate the high wheel loads of the new jet powered bombers, the B-47 and B-52
- Air Force and Corps planners first responded by increasing pavement thickness requirements in ‘channelized areas’ by 25%.
- Further analysis revealed that pavement *channelization was more a product of densification of pavement and insufficient compaction* than of pavement thickness.
- Subsequent recommendations provided improved asphalt mix and compaction specifications.

The YB-52 was a giant leap in scale over the heaviest World War II bombers shown here next to it, a B-17 and B-50 (background).

B-52 wheel arrangement

- **A B-52 weighs 172,740 lbs empty, and loaded, can weigh as much as 488,000 lbs**
- **Designers spread the bomber's weight over eight main gear tires (as opposed to only four on the B-47), grouping them four abreast (as shown at left), and using tire pressures of 260 psi**

The B-52 was equipped with tandem gear that could be swiveled in to provide crabbing for cross-wind landings

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Soil Runway Stabilization

C-130 dropping pallets using low altitude parachute extraction system during the siege of Khe Sanh in Vietnam

Re-grading ruts on earthen runway in forward operating area

Spraying RhinoSnot on rough graded runway for dust suppression

Dust cloud created by reversing turboprop engines on touchdown rollout

Limited conflicts in remote locations like Southeast Asia exposed the need for dust suppression and soil stabilization techniques to handle tactical airlift loads, shown here.

Boeing 707-80 high flotation tire tests at Harper Dry Lake in the Mojave Desert in 1964. It was chosen because it is a "wet" dry lake, with a thin crust about an inch thick, above a soft silt bed. The aircraft's tires sank about 6 inches (shown below).

This is why military transport aircraft are designed with much lighter wheel loads: to allow them to deploy on hastily constructed soil-cement runways in time of war. Runway constructed by the 864th Engineer Battalion in Operation Iraqi Freedom-2003.

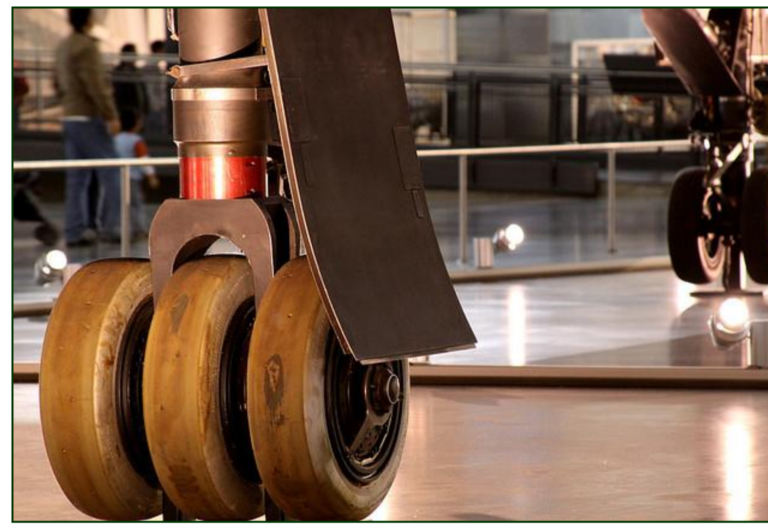
- **Above right: C-130 Hercules landing on a soil cement runway constructed by Army Engineers in Iraq in 2003.**
- **Above left: Landing tests using Boeing 707 on soft desert soils were carried out in 1964, by doubling the number of tires and reducing the tire pressure by 2/3, down to just 46 psi.**
- **These test were carried out when the C-5A military transport was being developed, to evaluate the military specification requiring the massive aircraft to be capable of landing on 'soft graded surfaces.'**

More pavement tests in mid 1960s

The Lockeed-Martin C-5B Galaxy has a maximum takeoff weight of 769,000 lbs, supported on 32 tires

- **Upper left: 100,000 lb test carriage developed by the Corps of Engineers to simulate the wheel loads of a C-5A Galaxy, for pavement design**
- **The special tires on the simulator were 8 ft diameter and 3.5 ft wide**
- **Lower left: C-5's were originally equipped with 28 tires, using 128 psi air pressure on hard runways. In service the aircraft employs a tire pressure of 115 psi, considerably lower than other jumbo aircraft.**
- **The tire pressure can be reduced from inside to cockpit to accommodate landings on soft surfaces.**

Highest Aircraft Tire Pressure



The highest aircraft or vehicle tire pressure ever employed in near-constant use was the supersonic Lockheed SR-71 Blackbird, which was capable of flying at speeds of Mach 3.2+. It had a maximum takeoff weight of 170,000 lbs distributed on eight tires, with tire pressures of 415 psi!

Part 4

COMPACTION TESTING

Runway Repairs

- Procedures were developed during the Second World War to run density tests in granular mixtures, and specify repairs and spot patches. These pictures are from Iwo Jima in July 1945

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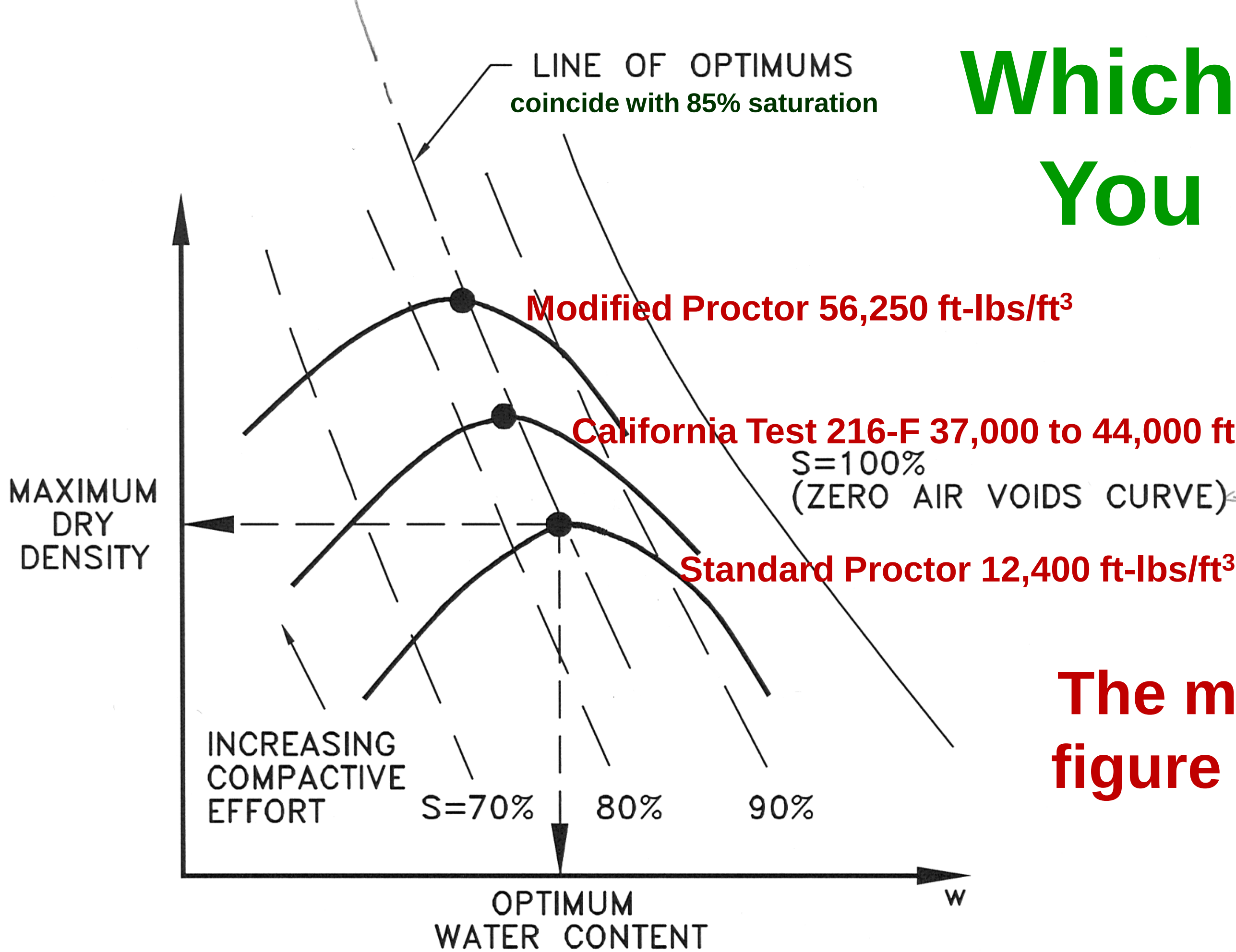
Which Test Are You Using?



The most important figure in this lecture

- **Compaction tests results vary with the input compactive effort**, usually measured in foot-pounds per cubic foot of soil.
- The line of optimum moisture contents is usually around 85% saturation and the optimum moisture content decreases with increasing compactive effort.

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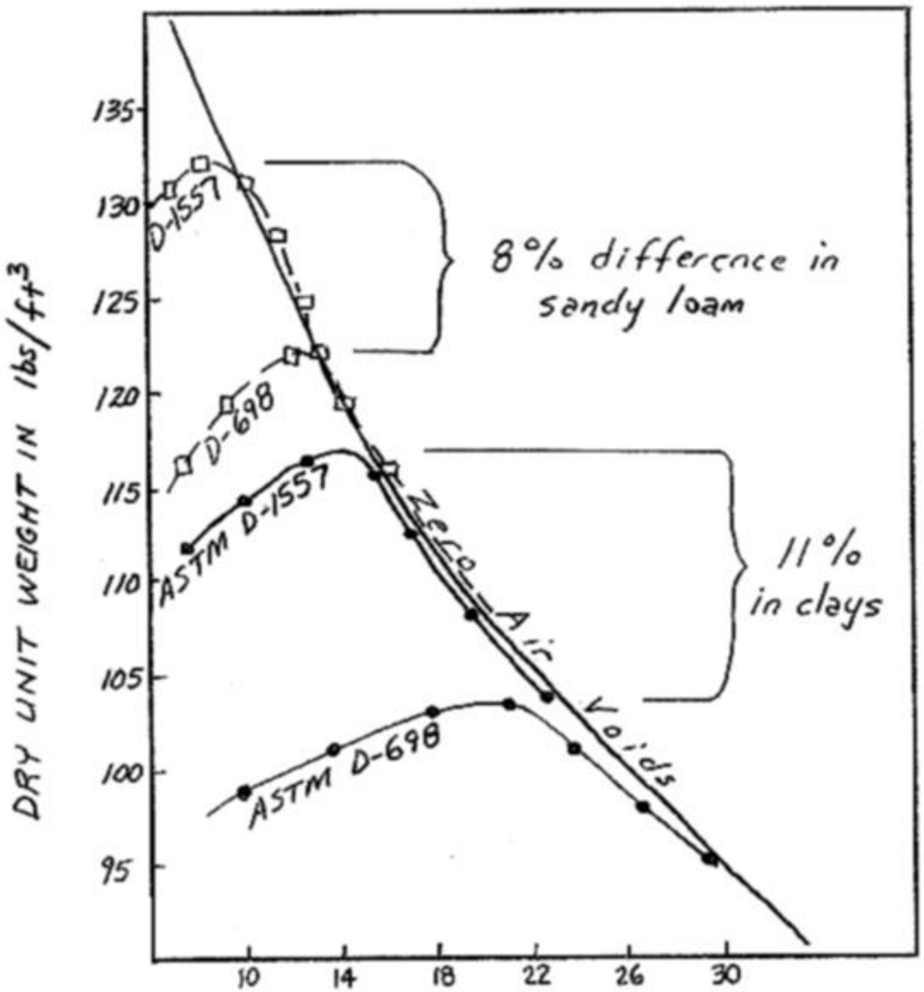
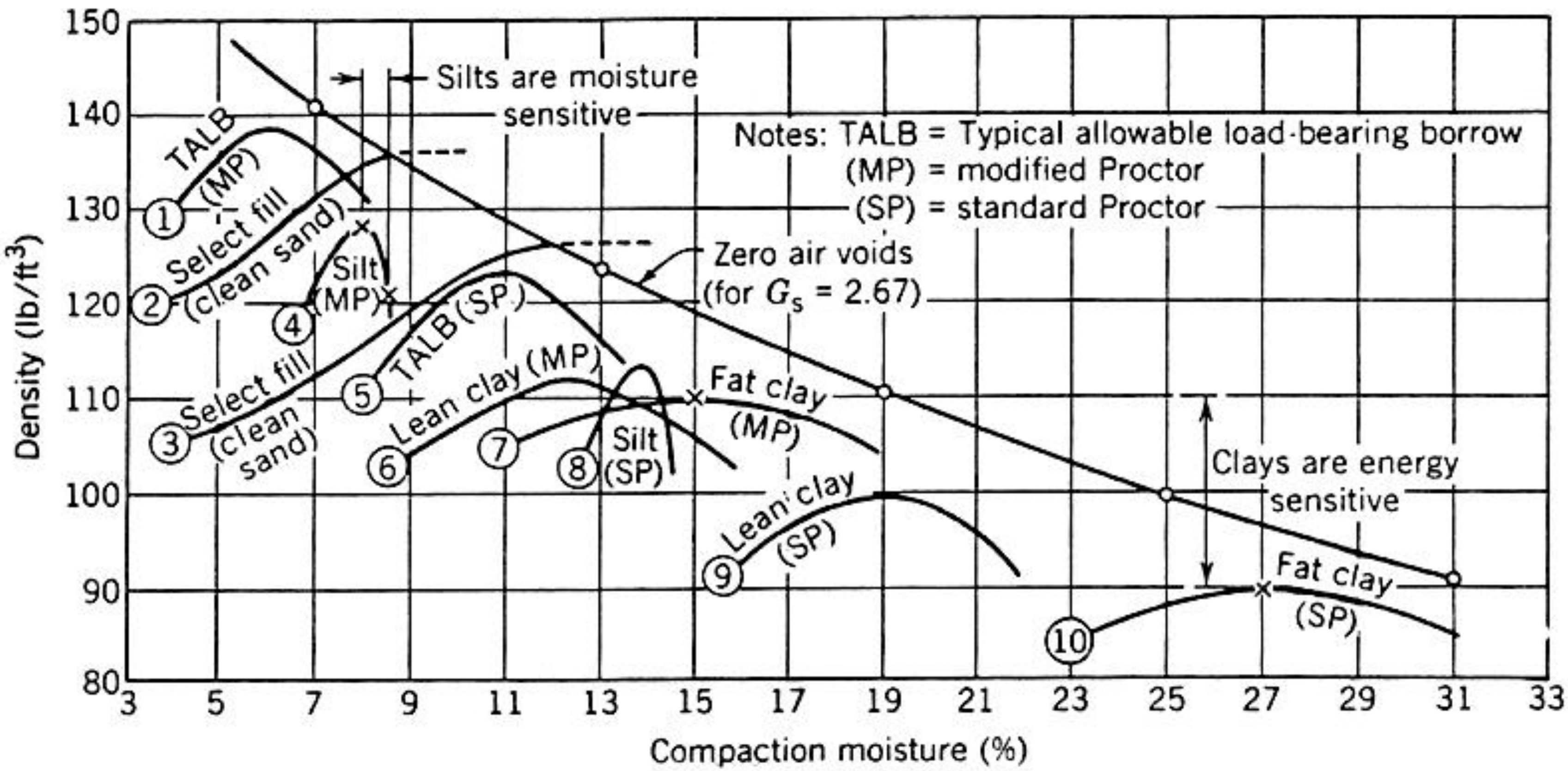
Comparison Between ASTM D-698-70 and ASTM D-1557-78



- **The Standard Proctor test (ASTM D698) employs 12,400 ft-lbs/ft^3 of soil, while the Modified Proctor (ASTM D1557) uses 56,250 ft-lbs/ft^3. This typically leads to variances between 8% and 11%, as shown above.**

SPECTURM OF CURVES



- **The** **maximum achievable density** **depends on the type of material, as well as the input energy during compaction. It is commonly used for diatomaceous earth and halyositic clays.**

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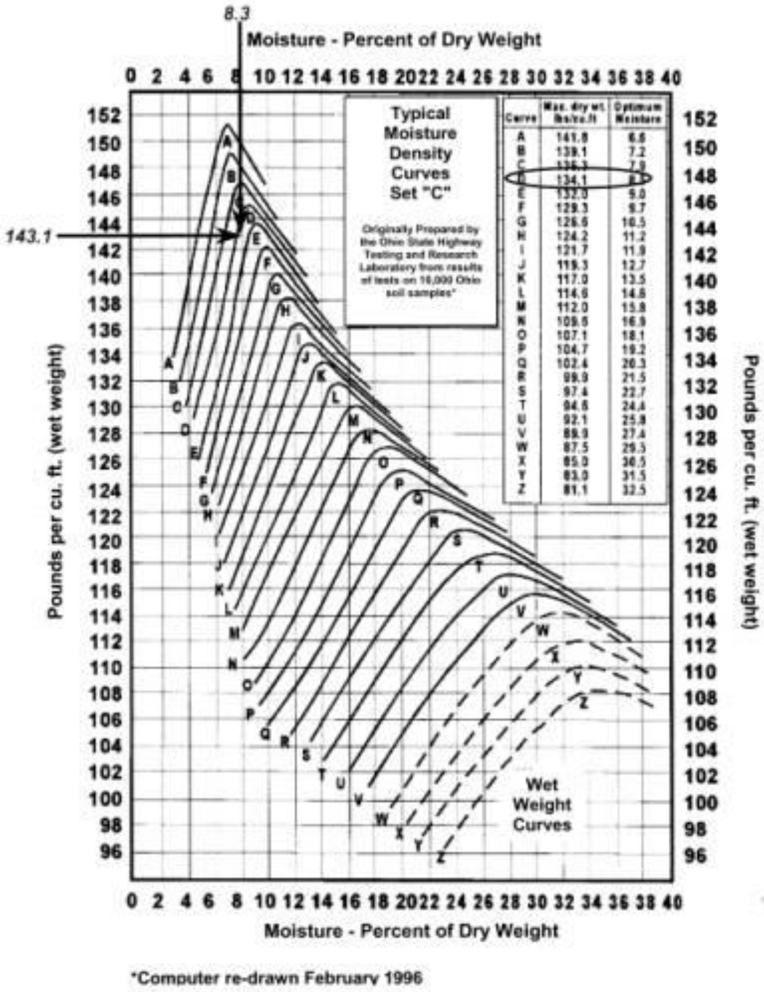
Curve Fitting and Speedy Moisture Meters



- Family of **expected wet density compaction curves**, based on 18,000 compaction tests compiled by the Ohio DOT

The **Speedy Moisture Meter** is a portable system comprising a vessel with an integral pressure gauge a weighing scale in a portable case.

A small sample of the material is prepared, weighed and
placed into the vessel. The reagent is then added and the vessel is sealed and shaken to mix the reagent with the sample.

- **Compaction curves should be prepared for all types of soil in the project area, before earthwork commences.** If different soils are mixed, then “check points” should be calculated to ascertain the optimum moisture level for the soil mixture being placed and tested. A great deal of judgment is required when performing such work.

- Most field compaction tests are now made using nuclear density gages that employ a cesium element.
- Nuc gages can have significant errors if the extendable probe is located next to a rock > 3 inches across. In rocky fills the operator should always rotate the probe 90 degrees and take a second reading, recoding the lower of the two values.

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Part 5

AGING OF FILL

- **Wick drains** or **sand drains** can be used to hasten primary consolidation through drainage and surcharging. Modern wick drains employ heat-welded geotextile filter cloths wrapped around plastic "straws," which are pushed vertically through the soil, using a pile driving mandrel (shown at left).

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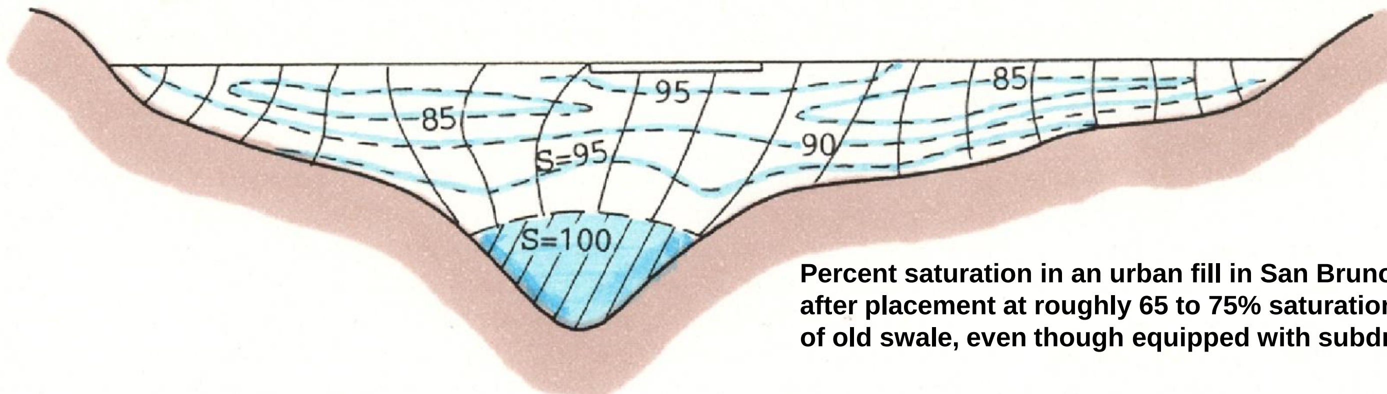
LONG TERM MOISTURE ABSORPTION



Percent saturation in an urban fill in San Bruno, CA 26 years after placement at roughly 65 to 75% saturation. Not saturation of old swale, even though equipped with subdrainage.

- **Urban embankments tend to absorb moisture with time, but complete saturation is usually limited to near-surface areas subject to landscape irrigation and infilled channels, like that shown above. This sketch depicts percent saturation of an urban fill in San Bruno, CA about 26 years after placement (from Rogers, 1992).**

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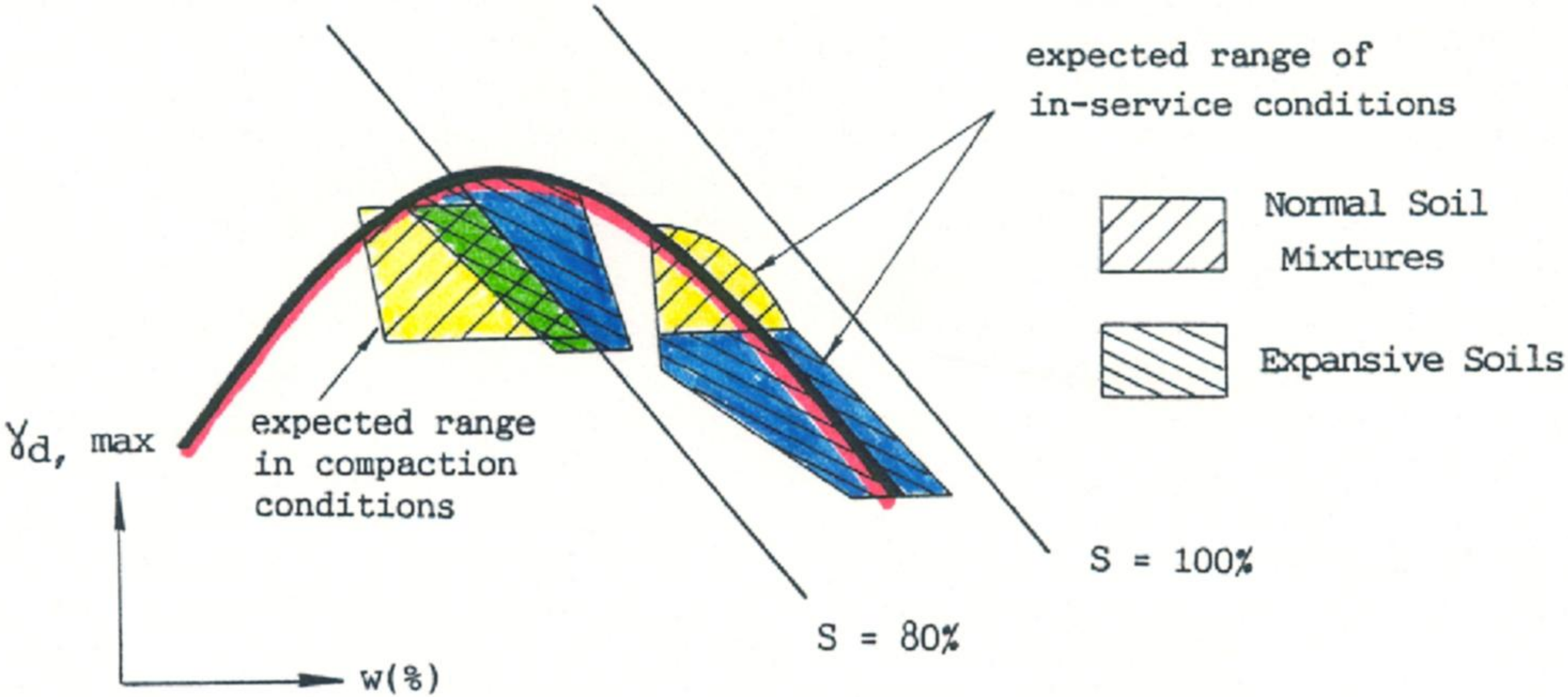
IN-SERVICE CONDITIONS



- **Compacted fill deeper than the zone of seasonal drying tends to absorb moisture with time, becoming softened and less dense. You cannot make assessments of soil density during construction years later because the moisture content increases (from Rogers, 1998).**

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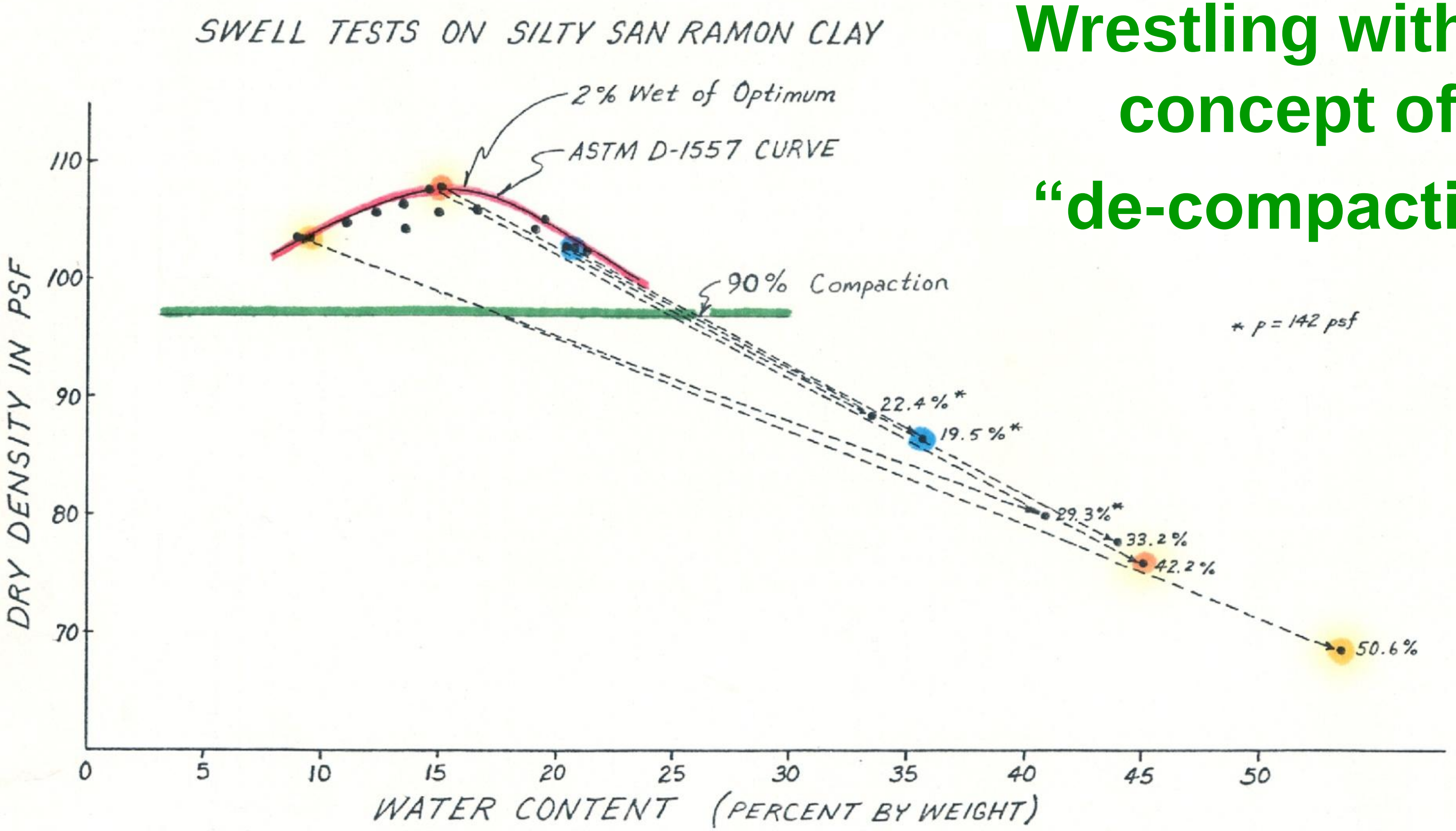
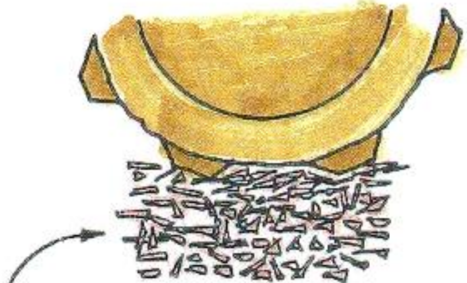
Wrestling with the concept of "de-compaction"



- **Expansive soils can swell > 50% if compacted on the "dry side" of the compaction curve, as shown in these data.**
- **Insitu field densities determined years after placement are <u>not</u> valid indicators of the original compactive effort** (from J. D. Rogers, 1998, Hydrocompression and Hydroswell - New terms in the geotechnical dictionary: in J.W. Borchers, ed., *Land Subsidence Case Studies and Current Research*: AEG Special Publication No. 8, pp. 119-147).

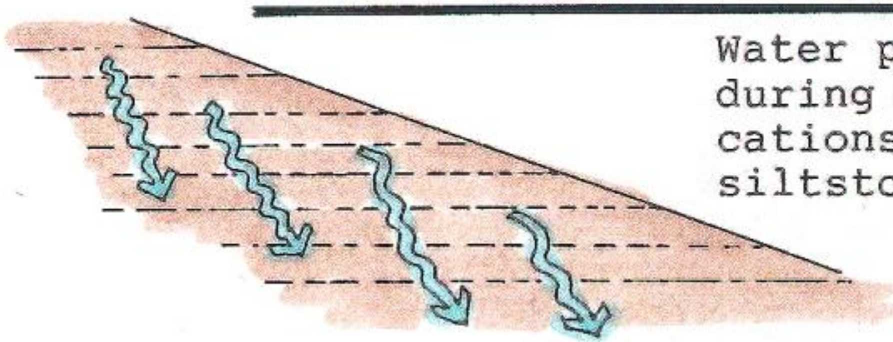
DURING COMPACTION



Pressures of up to 230 psi can be exerted by vibratory sheepsfoot compactors. Disaggregated bedrock particles are sufficiently strong to easily support heavy equipment.

Individual Particles engender a high specific surface area.

FOLLOWING CONSTRUCTION



Water percolates thru the embankment during winter months and exchanges cations with the disaggregated siltstone/claystone particles.

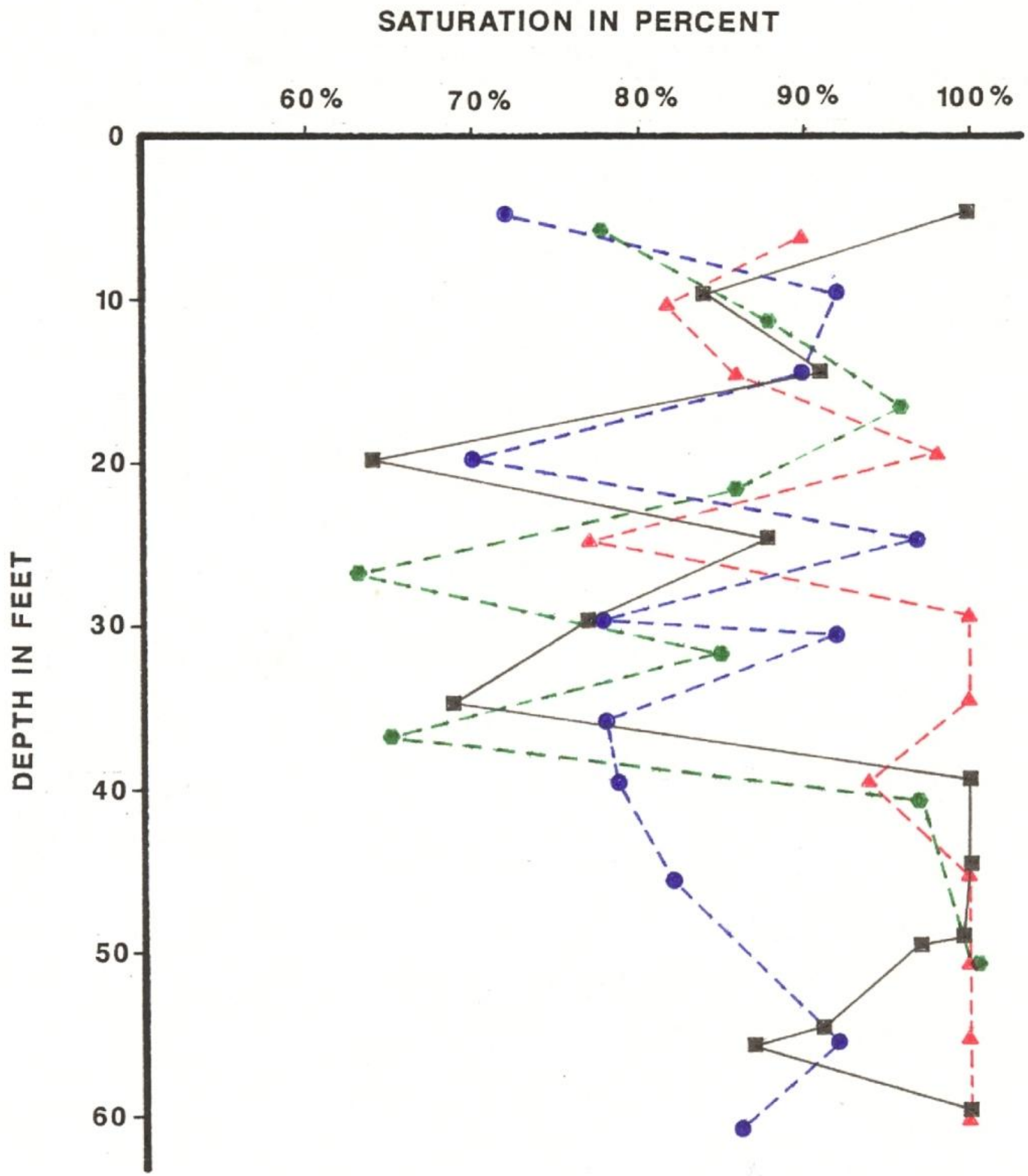
10-25 YEARS LATER

DISAGGREGATED SILTSTONE → CLAYEY MUSH

high water retention

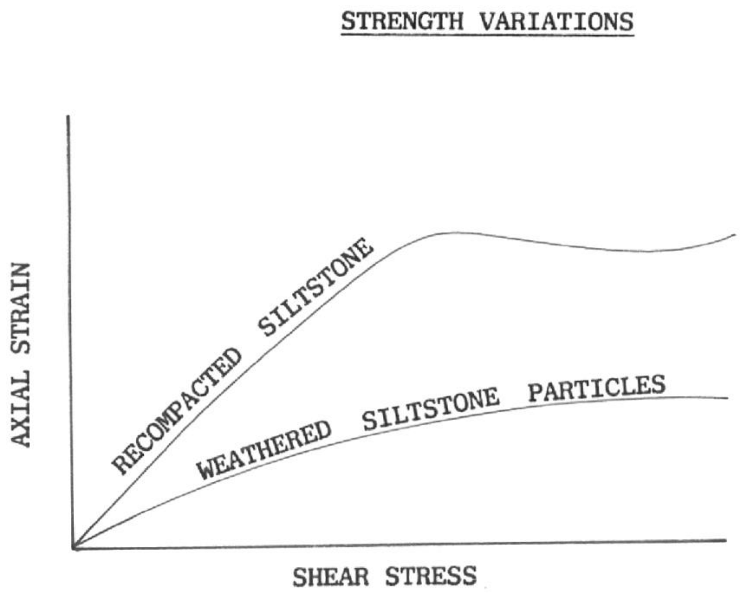
high water content

low strength

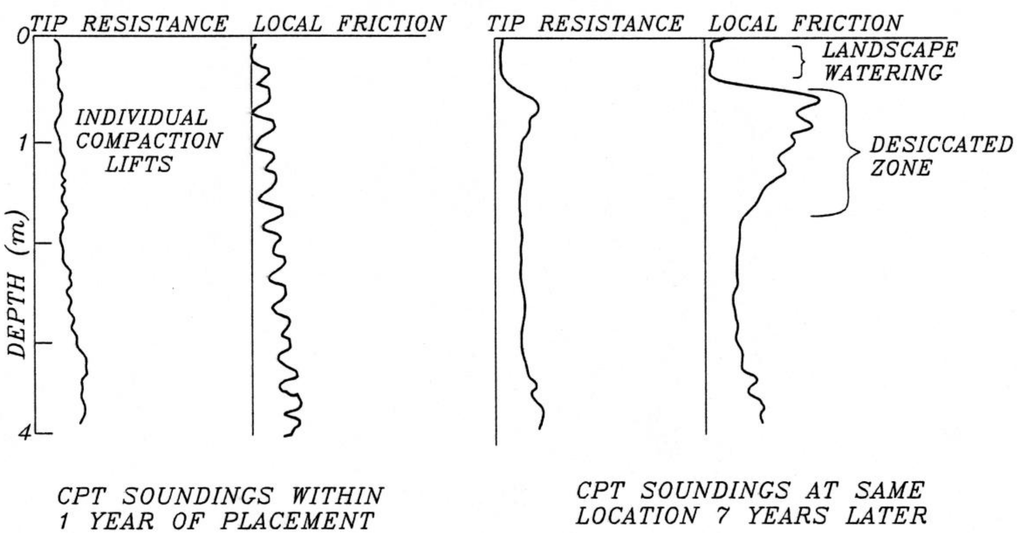


- Comparison of percent saturation with depth in an urban fill
- Blue and green data were taken from construction records (as constructed)
- Black and red data were measured 7 years later
- Note increase in moisture content

LOSS OF STRENGTH WITH INCREASING MOSITURE CONTENT OF FILL



Direct shear tests on Briones formation in Walnut Creek, California, at time of placement, and 23 years later.



- Fills comprised of finely disaggregated particles can absorb large volumes of moisture over time and noticeably soften, often exhibiting marked strength loss (above left).
- Lower left: CPT soundings on same lot illustrating the change in behavior of compacted silty clay in Blackhawk, California, after severe cycle of desiccation, followed by development and landscape watering.

Part 6

COMPACTION EQUIPMENT


The first Buffalo-Springfield steam rollers appeared in 1891.


1939 Ingersoll Rand 3-drum roller


4-ton Galion 'Rollamatic' tandem steel wheel roller, produced in Galion, Ohio -1943


Huber 12-ton Roller produced in Marion, Ohio – 1940s

Early Smooth Drum Rollers - Smooth drum rollers evolved from steam powered road rollers of the 1800s. Smooth drum rollers work best for well-graded granular soils of low plasticity, gravel subbase mixtures, and A/C pavements.

UMR

RUBBER TIRED ROLLERS

- **Rubber tired (pneumatic) rollers exert a compactive effort *equal to the air pressure* in their tires (35 to 100 psi).**
- **They are generally employed on sandy soils and asphalt pavement.**

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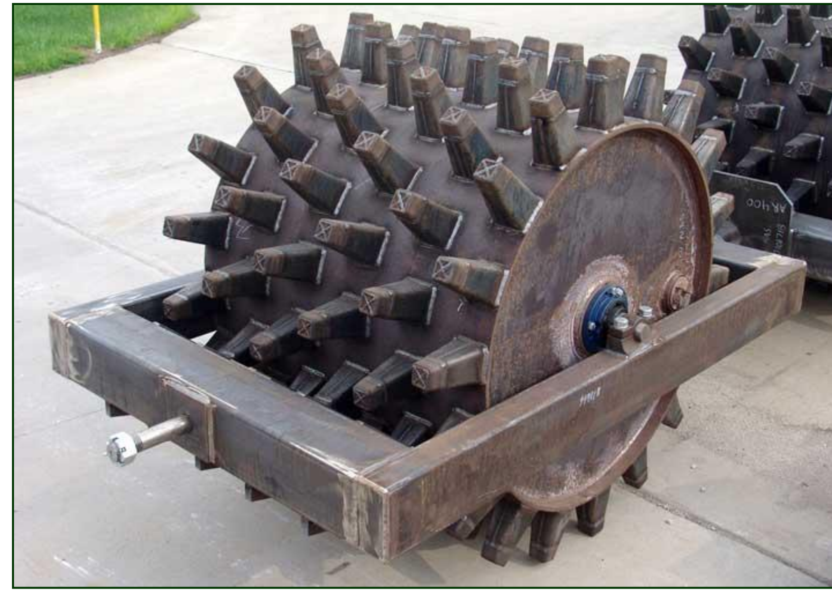
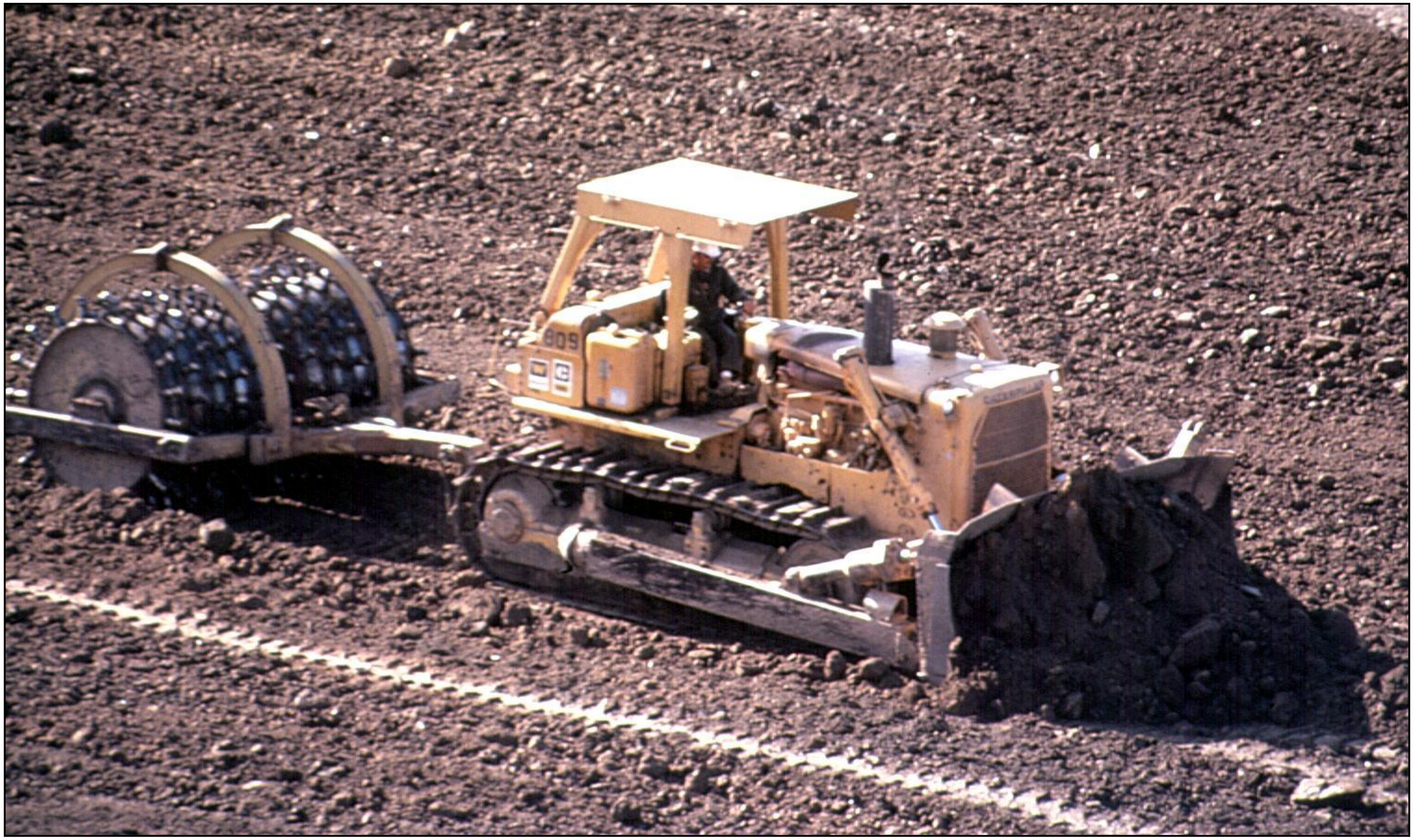
Paul Baumann (1892-1983) **supervised the design and construction of the San Gabriel Dam in 1935-38, for many years the highest rockfill dam in the world (355 ft) with a volume of 10,572,000 yds^3.**

- **The sheepsfoot roller has evolved into a wide variety of forms. This shows the Allis Chalmers roller, designed by Paul Baumann (above left), which introduced *replaceable* "hammerhead tips" in the late 1930s, during construction of the San Gabriel Dam by the Los Angeles County Flood Control District.**

- Left: **Spike rollers** are a sheepsfoot variant that can be employed to help break up and disaggregate soft or fissile bedrock materials, increasing the bulk density of the fill mixture
- Right: A common variant is the **flat head tamping roller**, which employs tapered 'box heads.' This variant places *three tips* normal to the ground surface at any given time

SHEEPSFOOT ROLLERS



- **Light standard sheepsfoot roller, with 42-inch diameter drums weigh between 8000 and 16000 lbs per 8 ft width and exert contact pressures from 1000 to 300 psi, with spike contact area of 5 to 8 square inches. The spikes compact a zone 2 to 8 inches beneath their tips. This roller first appeared in California around 1930.**

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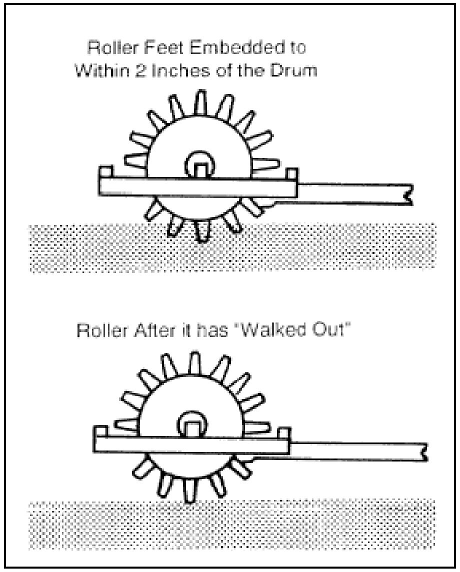
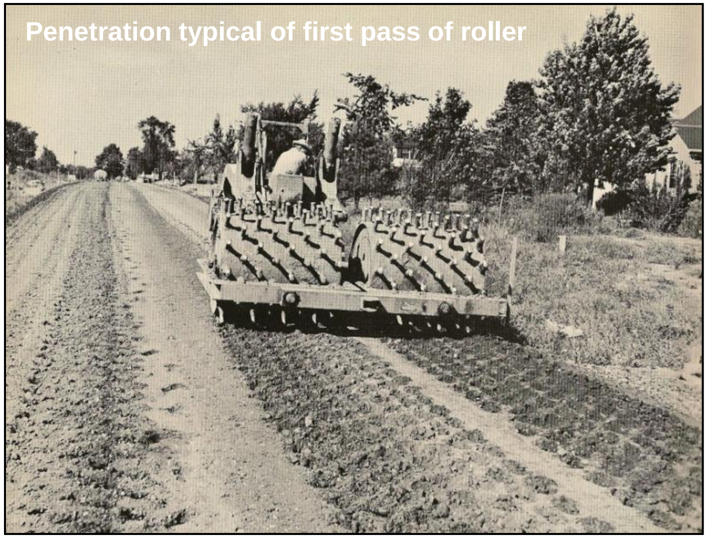
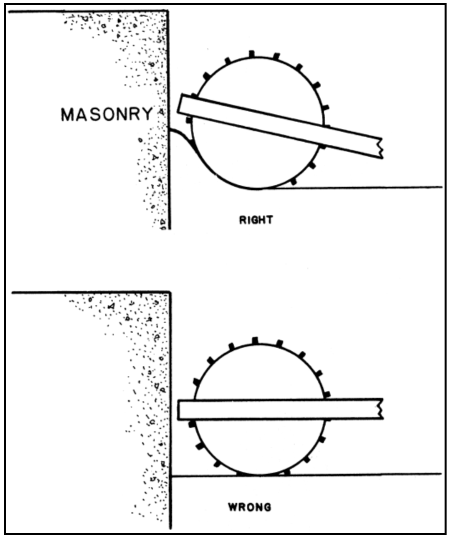




Almost idiot-proof: Any cat skinner (dozer operator) can be taught to "walk" his sheepsfoot roller out of the soil being compacted, as shown in these images.



Roller wheels cannot compact soils within ½ roller diameter of a vertical surface, such as wall or trench

- **Upper left: Sheepsfoot rollers "walk out" of the soil as it becomes densified, *leaving the uppermost 1 to 2 inches uncompacted (don't test the upper two inches – ever!)***
- **Above middle: For this reason it is important that cohesive soils be scarified prior to compaction (difficult if scrappers have been running over everything)**
- **Lower left: Roller compactors cannot compact soils adjacent to walls or near-vertical cuts. Compaction can be achieved by ramping the soil up against the wall (shown here) or inclining the backcut at 45 degrees or less.**

Letourneau Compactors

- Upper Left: In 1947 Letourneau introduced the Tournadozer, or wheel dozer, shown here. It allowed higher speeds (13.5 mph) spreading and compaction of fill lifts, using the air pressure of its enormous tires. Letourneau produced three models, all weighing approximately 25 tons, a 300 HP engine, and a 5.5 cubic yard blade capacity.
- Lower Left: The short-lived Tournapull Roller was developed for the highways market in the early 1950s to provide kneeding compaction of clayey soils with high speed and maneuverability, over long distances.

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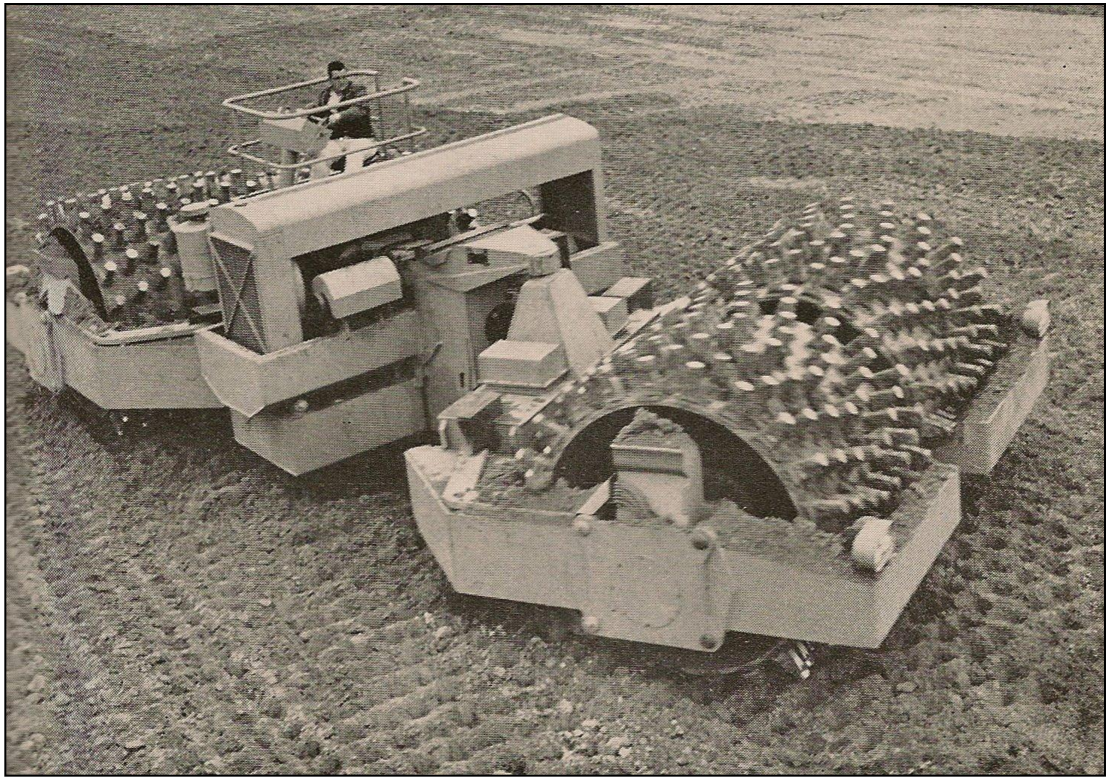
The first self-propelled compactors



- Letourneau introduced the first self-powered soil compactor in March 1959, which were improved and produced up thru 1966.
- Known as the M-50 Power Packer series, they weighed 45 tons, employed an articulated chassis, and were powered by a 420 hp Cummins V-12 engine providing current four electric motors driving the wheels. Only 35 were produced, but they influenced Caterpillar to design and fabricate something similar

CAT 814, 824, and 834 Series wheeled dozer-compactors


Older CAT 834B with straight blade

In 1963 CAT introduced their 824 Series wheel dozer line with a 300 hp diesel engine and the more powerful 834 Series with 400 hp engines (upper right). In 1970 they introduced the smaller 814 series wheel dozer, with 170 horsepower (shown below). The products went through multiple upgrades over the next two decades, culminating with the 814F, 824G, and 834B models in 1997. That year CAT added two more models to their line, the 844 and 854G. The CAT 834B Series (shown at left) weigh 104,000 lbs C18 diesel with 500 hp


1968 CAT 834A

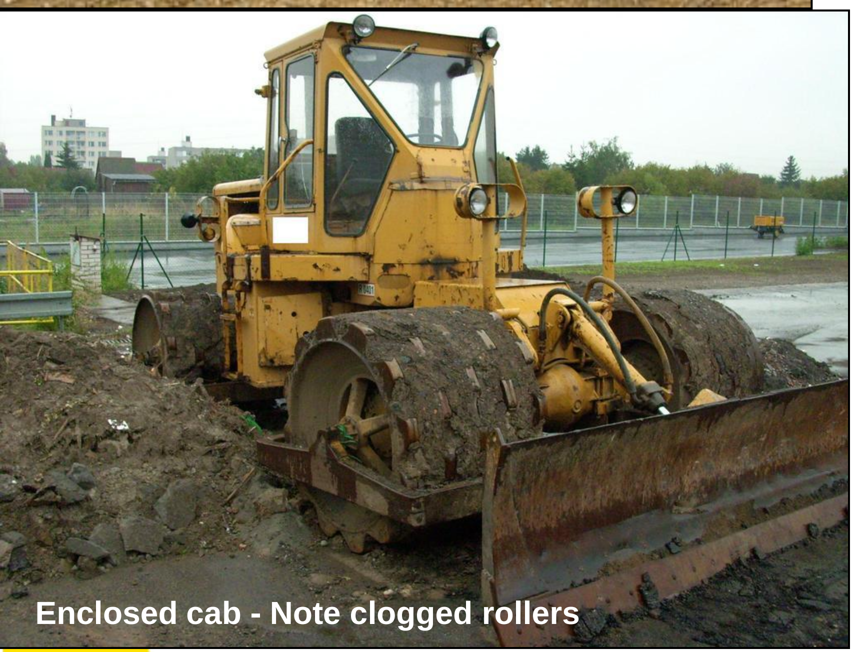

CAT 834B with U-shaped blade

CAT 814

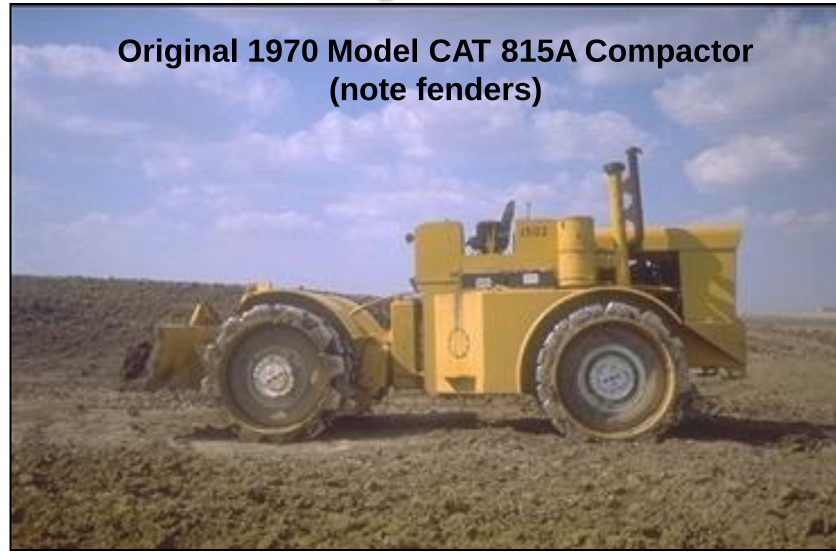

Though not common, the 814, 824, and 834 series wheeled dozers can be retrofitted with pad rollers, as shown at left

CAT 815 series compactors

815B with roll-over protection


Enclosed cab - Note clogged rollers

Original 1970 Model CAT 815A Compactor (note fenders)



The Caterpillar 815 Series self-propelled compactors first appeared in 1970 and the rollover protection systems introduced in 1971. The 815 employed a D333 turbocharged engine producing 170 hp, with articulated steering and 4WD. This series is still in production with the 815F.

Always watch for clogged rollers (lower left) on the series 815s, 825s, and 835 compactors, before cleaning teeth were installed

CAT 825 Series

Note muddy wheels

The 825C series is the most numerous, produced between 1981-95

Production began in 1969 with a D343 turbocharged 6-cylinder engine producing 300 hp.

It employs a powershift transmission and electric start and comes standard with articulated steering, and all-wheel drive on the compactor wheels.

Mud teeth remove accumulated soil between roller pads

Left: The 825H series is still in production. Its all weather cab is equipped with heating and air conditioning 15 ft wide blade and 5.5 ft diameter wheels

Notes: In 1980 CAT added headlights; in 1984 a folded core was added. 1992 saw the introduction of full suspension seats with retractable seatbelts. In 1993 the exhaust manifolds were modified with longer mounting studs and spacers. CAT offered a certified rebuild program with this model, which are widely used, world-wide. The 825 G series was produced between 1996-2002. The operating weight is 72,164 pounds.

CAT 835 SERIES COMPACTORS

- **Above: The CAT 835 series self-propelled compactors were manufactured between 1969-73. They employed a D343 turbocharged after-cooled six-cylinder engine producing 400 hp.**
- **CAT 835s can be fitted with different kinds of rollers, a shown here. The machine at upper left has a pad roller while the one at upper right employs actual sheepsfoot roller pins.**
- **Lower Left: CAT 835 pad roller with enclosed all-weather cab**

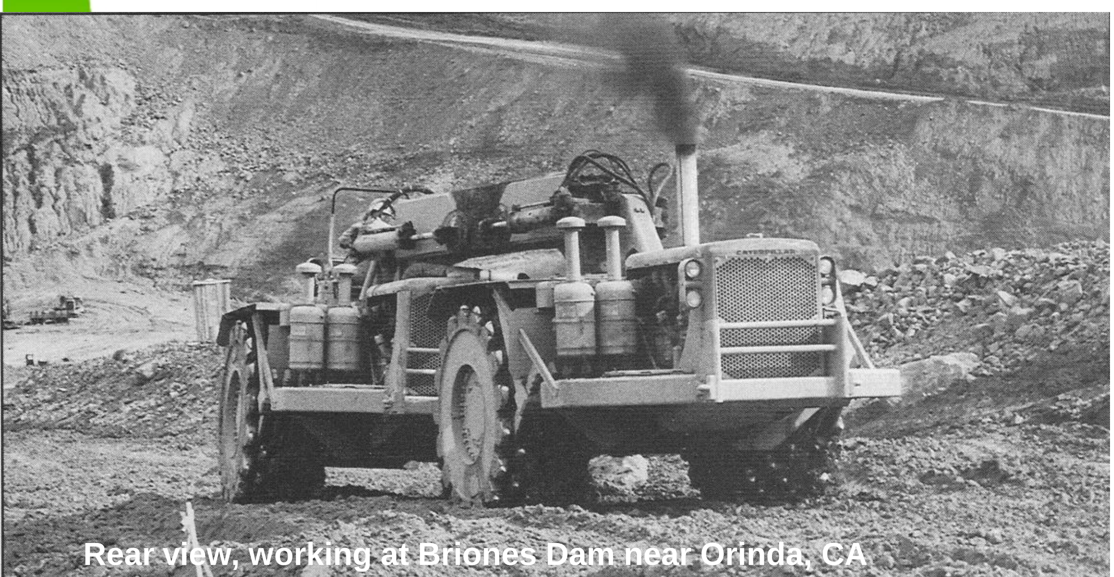
Landfill Compactors

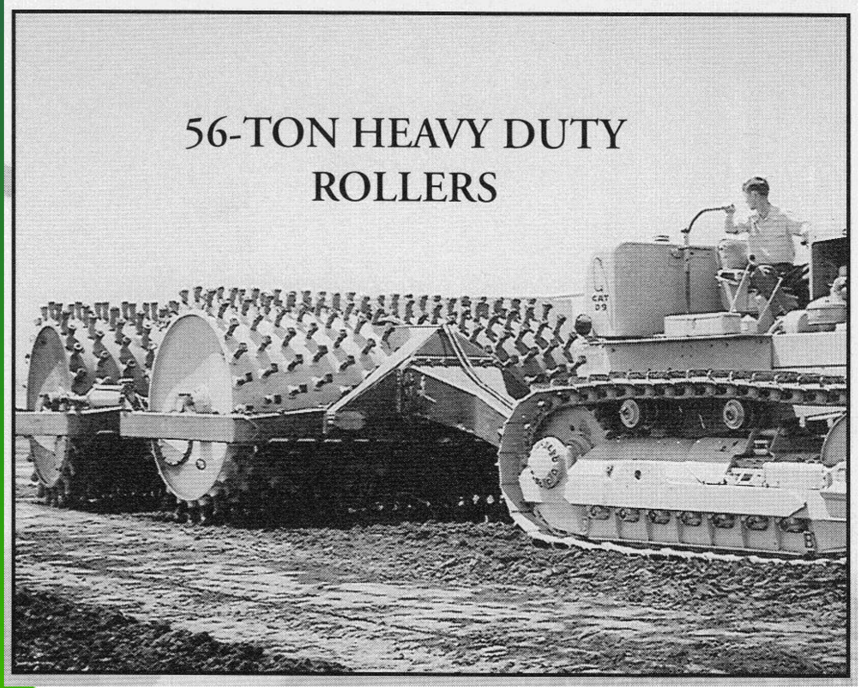
A range of specialized landfill compactors have appeared on the market over the past 40 years, by most of the major manufacturers. These employ various types of wedges and cruciform shapes designed to disaggregate solid waste and integrate it with soil fill. These are not intended for use on engineered fill.

Hybrid Compactors

Above left: CAT 621B Scrapper converted to a padfoot roller compactor for highways work, where the distances are considerable.

Below: Converted CAT 631 scrapper dual-drive pad compactors built by Peterson Caterpillar in San Leandro, California for Guy F. Atkinson Company, and used on the Briones and Oroville Dams in the 1960s.


Rear view, working at Briones Dam near Orinda, CA



Large Special Duty Compactors

- **Upper image: Specially-built 56-ton heavy duty sheepsfoot rollers built for earth dam construction by Guy F. Atkinson in the 1960s.**

- **Lower image: 50 ton multiple box pneumatic-tire compaction roller being used on the damaged runway at Oakland International Airport in 1989. Note box segments, which are semi-articulated.**

COMMON PAD ROLLERS

- **Self-propelled tamping or pad rollers are not sheepsfoot rollers. They are only capable of delivering 5 to 75 psi contact pressures.**
- **They are well suited to most soil mixtures and may employ vibration (2500 to 4500 Hz) for compacting cohesionless (sandy or gravelly) materials.**
- **They have a high center-of-gravity, which makes them more prone to overturning near slopes**

Impact Rollers

The roller weighs 35,700 lbs

- The latest compaction equipment are ***high-energy impact rollers***, which use shaped (*e.g.*, triangular ellipsoids or hexagonal), as opposed to round drums, as shown at upper right. The high energy imparted by these systems allows them to achieve compaction at a faster rate and to greater depths.
- A comparison of different types of compaction equipment based on vertical settlement with number of passes is shown at upper left, demonstrating the superior effectiveness, both in terms of number of passes, and influence depth of high-energy equipment.

Part 7

COMPACTION METHODS

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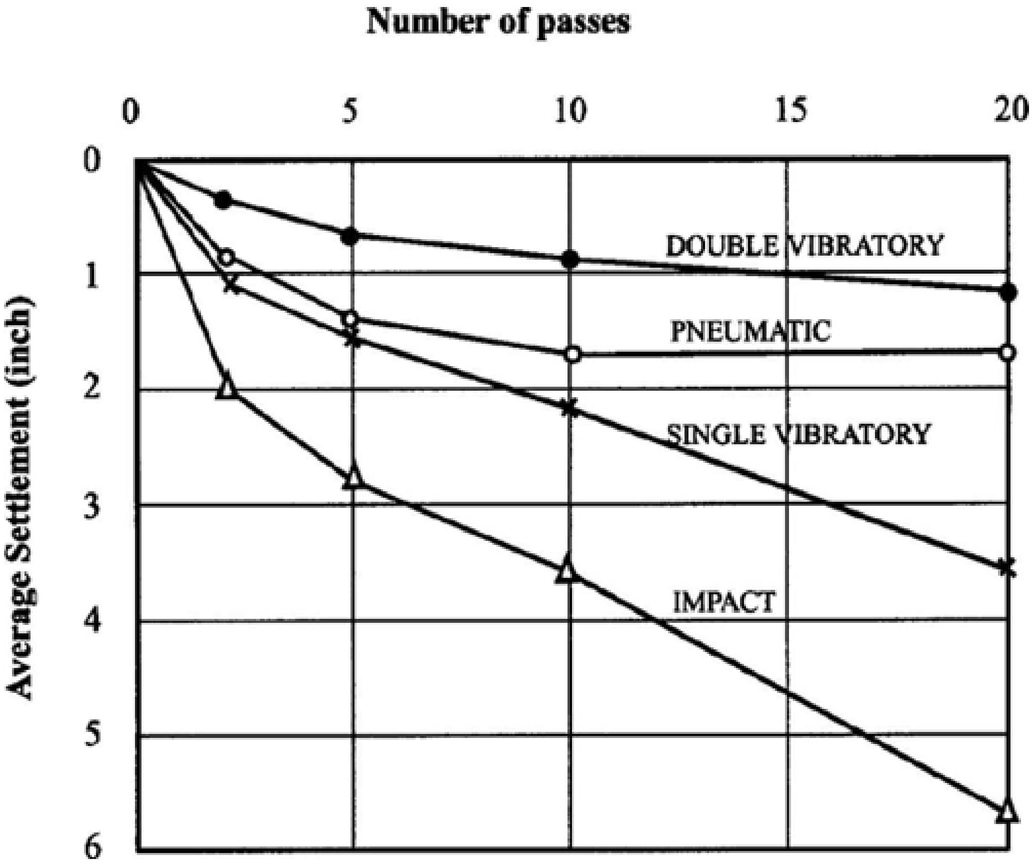
No. of Passes	Depth to 75% Rel. Density
2	1.7 ft
5	2.5
15	3.2
45	4.0

For Clays: Using a Self-Propelled Cat 837 Sheepsfoot Roller

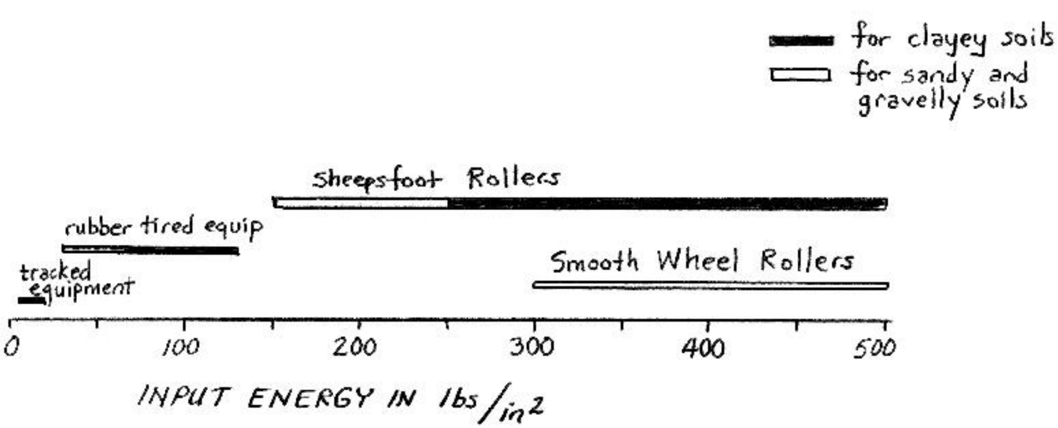
No of Passes	Depth to 90% of ASTM D-1557		
	3% dry of optimum	optimum moisture	2% over optimum
2	0.25	0.38	0.33 ft
4	0.42	0.54	0.50
6	0.50	0.67	0.60

- **The number of passes needed to achieve the desired compaction depends on the lift thickness, contact pressure, and soil moisture content.**
- **Most contractors get a feel for these figures, based on their local experience. If you are dealing with a contractor who has not previously worked in the area, you should be wary.**

ROLLER EFFICIENCY and CONTACT PRESSURES



- Number of passes versus average settlement (compression) in inches for various modern compactors. Note efficiency of impact rollers.



- Contact pressures/Input energy for various types of compactors. Note that track-walking fill with dozers is not an adequate means of compaction.

Recommended field compaction Equipment for different soils

(from Rollings and Rollings, 1996)

Soil	First choice	Second choice	Comment
Rock fill	Vibratory	Pneumatic	-
Plastic soils, CH, MH (A-7, A-5)	Sheepsfoot or pad foot	Pneumatic	Thin lifts usually needed
Low-plasticity soils, CL, ML (A-6, A-4)	Sheepsfoot or pad foot	Pneumatic, vibratory	Moisture control often critical for silty soils
Plastic sands and gravels, GC, SC (A-2-6, A-2-7)	Vibratory, pneumatic	Pad foot	-
Silty sands and gravels, SM, GM (A-3, A-2-4, A-2-5)	Vibratory	Pneumatic, pad foot	Moisture control often critical
Clean sands, SW, SP (A-1-b)	Vibratory	Impact, pneumatic	-
Clean gravels, GW, GP (A-1-a)	Vibratory	Pneumatic, impact, grid	Grid useful for over-sized particles

Reference: Rollings, M.P., and R.S. Rollings (1996). *Geotechnical Materials in Construction*, McGraw-Hill, NY

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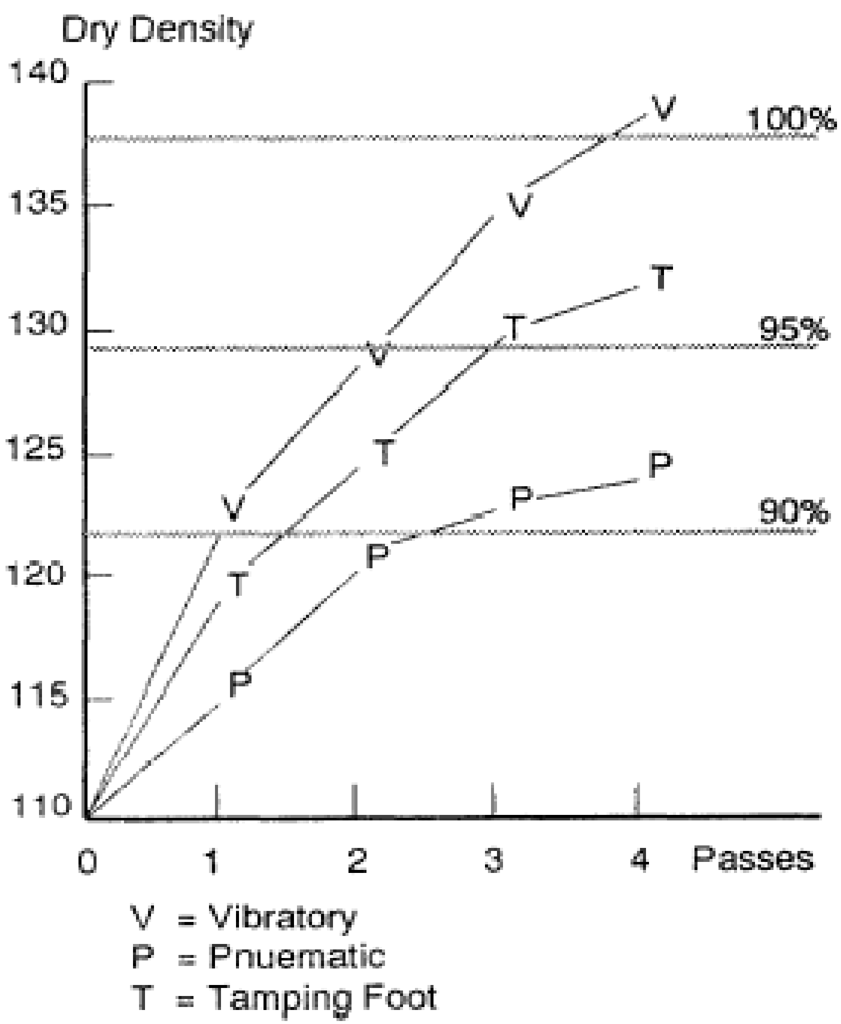
RUNNING TEST STRIPS



- Test strips are useful to determine which type of compactor and how many passes will be necessary to achieve the desired compaction
- In this example, P is pneumatic tire roller; T is a tamping foot, or pad roller; and V is a vibrating drum roller
- The example at left is for a granular soil mixture; which benefit from vibratory compaction

- **Vibratory plate** and **spiked or pad roller compactors** (at right) can be attached to tracked excavators to provide mechanical compaction of trench backfill, mostly for buried utilities. These trenches are not usually compacted in 6 to 8 inch lifts, so can settle noticeably.

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- The diesel powered Ramex P/33 Trench Compactor is hand-operated and used in trenches and difficult access areas.
- These walk-behind and remote controlled compactors weigh about 3000 lbs and were developed for compacting backfill in pipeline trenches more than 27 inches wide
- They typically exert between 10 and 18 psi contact pressures at frequencies around 62 cycles per second (Hz), necessitating lift thicknesses of no more than 4 or 5 inches.

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REMOTELY OPERATED MINI-COMPACTORS

- Remotely-operated mini-compactors have taken over the burden of trench backfill compaction operations
- These machines only engender about 10 to 14 psi compactive effort

Hand Operated Tampers and "Pogo Sticks"

- Hand-operated tampers, like this *Wacker BS 700*, typically exert compaction contact pressures between 7 and 18 psi
- Tampers are only useful for compacting soils in lifts 2 to 3 inches thick at near-optimum moisture content, if trying to achieve 90% of the ASTM D 1557 compaction standard

Vibratory Plate Compactors

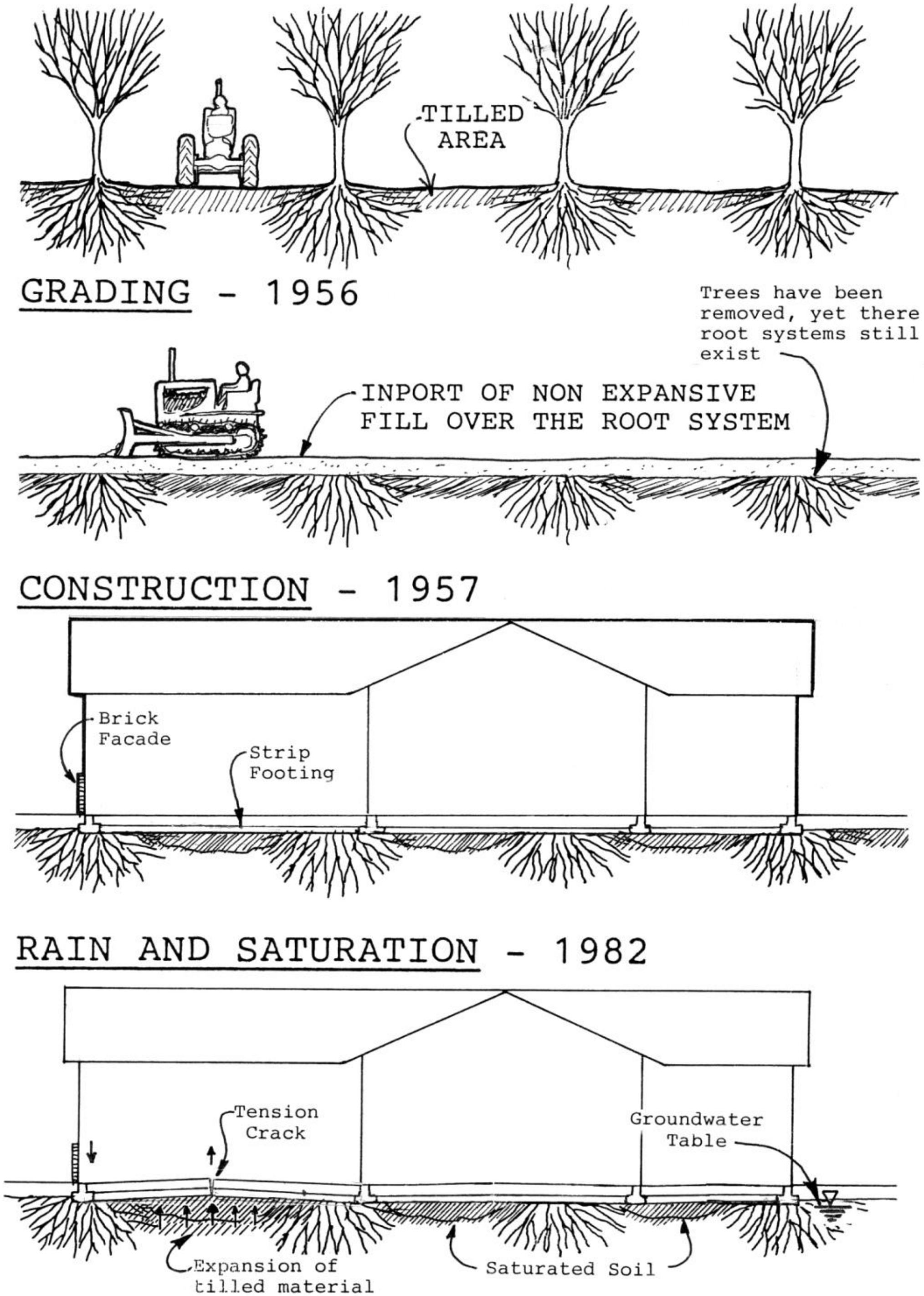
- Above left - This *Wacker VP1340A Plate Compactor* only weighs 170 lbs, but only exerts a dynamic contact force of 5 to 7 psi, using 63 Hz frequency
- Lower left - This *Bomag plate compactor* weighs 726 lbs and exerts a compactive force of 13 psi, at 62 Hz frequency.

Part 8

COMMMON PROBLEMS

INSUFFICIENT GRUBBING

- **Established compaction standards limit inclusion of organic debris to *no more than 2% by volume* if less than 2-inches diameter, and zero percent for debris > 2 inches in diameter (Mike Scullin in photo)**



ENTRAINED ORGANICS

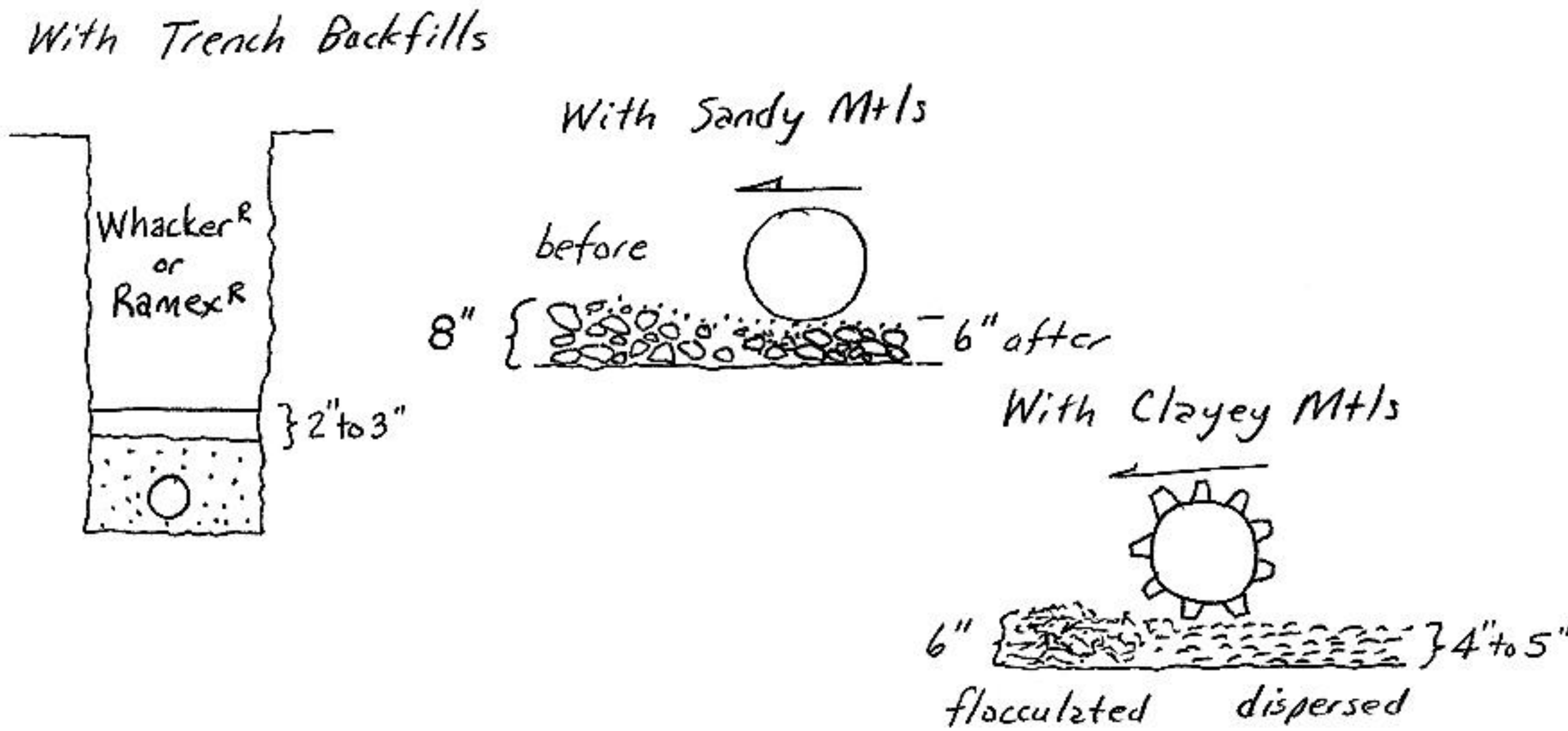
- **Root balls left in the ground usually rot within 5 to 10 years, leaving noticeable pockets of settlement or sinks structures if the voids collapse**
- **In this case the tilled furrows between the root balls heaved upward, breaking the lightly reinforced house slabs**

Always try to employ the

Observational Method

- **Common sense and the observational method are crucial components of soils testing. If you see a lot of dust blowing during grading, chances are the fill is being placed well dry of optimum moisture level.**

WATCH FILL LIFT THICKNESS



- **Lifts between 6 and 8 inches are typical when using standard size compactors. This thickness must be reduced if using smaller hand-operated machines, as is often required in trench excavations.**

Speed vs lift thickness

- The faster the scrapper moves during fill placement, the thinner the lift of soil that is laid down. This can be advantageous if the soil is near optimum moisture content and can be rolled between passes. Note how dry the working pad is in this image, and the slightly dusty nature of the fill being loosed upon this dry surface. Both these factors would lead to lower-than-optimum placement.

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BEWARE OF DOUBLE DUMPING

- These scrappers are dumping thick lifts of fill one behind the other. This is known as "*double dumping*" and should be prohibited when placing engineered fill.

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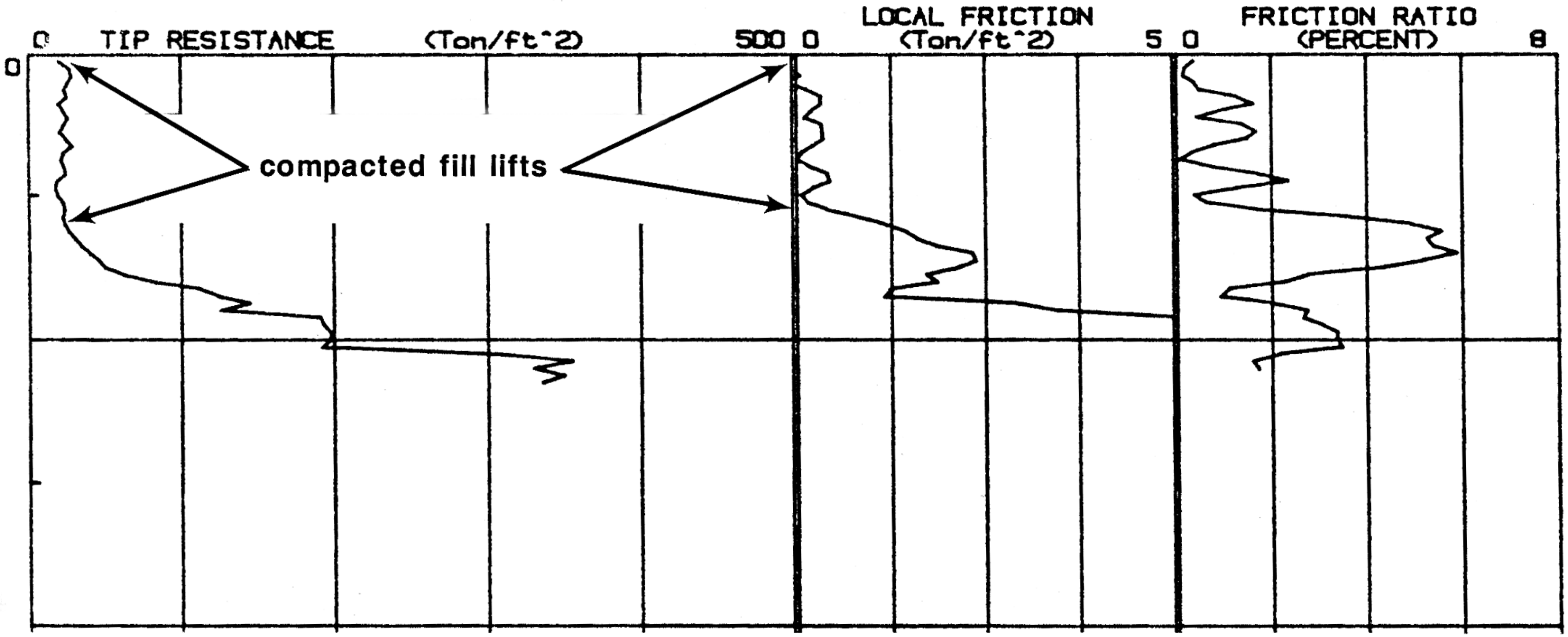

- **Fill lift thickness can be detected as cyclic variances in *sleeve friction ratio* of Cone Penetrometer Soundings made shortly after compaction, before the fill has absorbed noticeable volume of water** (from J. D. Rogers, 1992, Long Term Behavior of Urban Fill Embankments: Stability and Performance of Slopes and Embankments II: ASCE *Geotechnical Special Publication 31*, Vol. 2, pp. 1258-1273).

Failure to compact keyway margins and/or subdrains

- **CAT 825 series pad compactor spreading a lift of fill in a keyway using its blade. Fill lifts should be between 4 and 8 inches thick with a minimum of two passes by the compactor before placing more fill.**

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MOISTURE CONTROL

- **Moisture control** is of paramount importance when compacting cohesive soils, especially expansive soils. **Low humidity wind** is a bigger problem than ambient air temperature.

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The wetter the better for structures

- When compacting <u>expansive soils</u> to support structures (not roads), care should be exercised to compact the soil 2% to 5% *over* optimum moisture content, if possible.

UMR

- **When compacting expansive soils *wet of their optimum moisture content*, some sacrifice may need to be made. In situations with high plasticity clays (PI > 25) it may be advisable to employ a reduced density in the upper 5 to 10 ft of the fill prism, to reduce the potential for post-construction heave (Seed & Chan, 1959).**

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- **Oversize rock** can be included in engineered fill, provided proper precautions are taken to provide filtration between voids. This is usually accomplished by jetting a well-graded gravel mix (such as Cedergren's Class II permeable mixture) into the interstices between the blocks.

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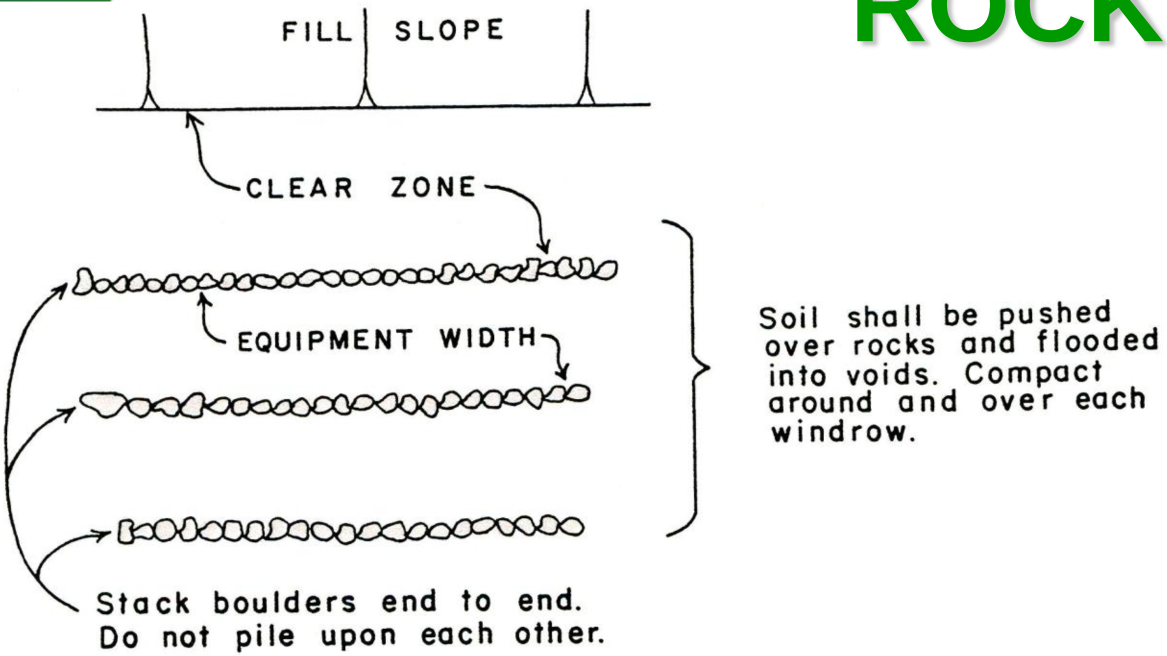
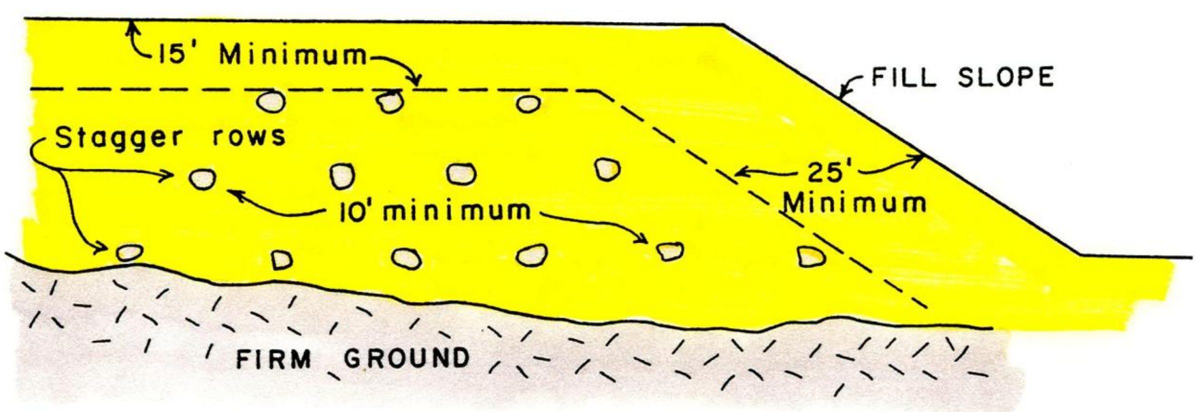
ROCK WINDROWS

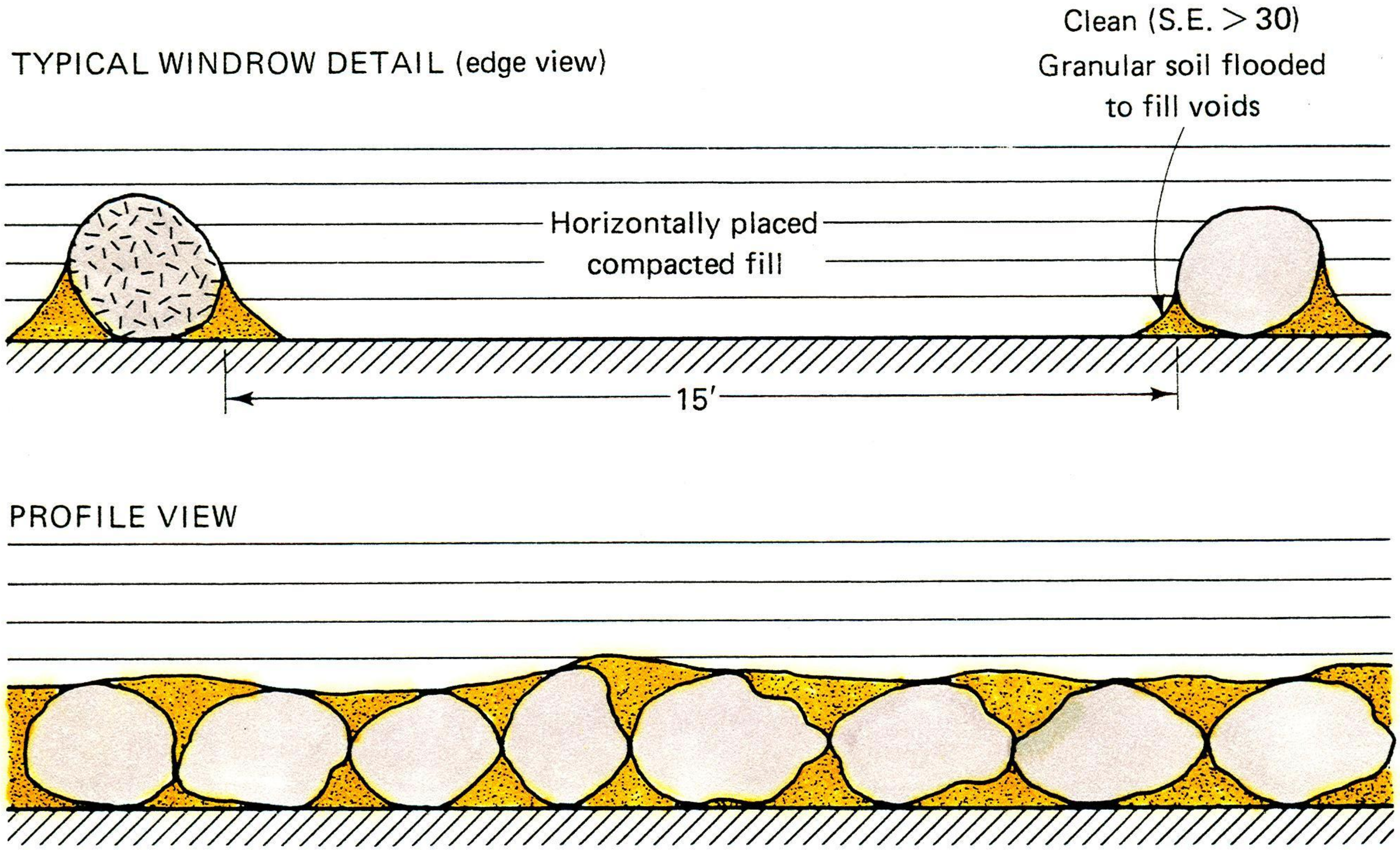


PLAN VIEW



SECTION VIEW

- Rock windrows are used to bury oversize rock
- Rocks are lined up in rows
- Rows are typically buried >15 feet below finished grade and >25 feet behind sloping face



- **Windrows are usually sluiced with jetted sand and gravel mixtures, to infill voids beneath and between blocks, as sketched here. Sluicing is important because it is impossible to compact beneath the rounded, irregular blocks.**

Sluicing well graded granular backfill

- ***Well-graded mixtures*** **of sand, gravel, and rock can be hydraulically sluiced by hoses and vibrated to generate sufficient compaction and interlocking, as shown at left. Target water contents are around 10% moisture**
- **This shows the backfilling of a reinforced concrete power conduit for the Bureau of Reclamation**

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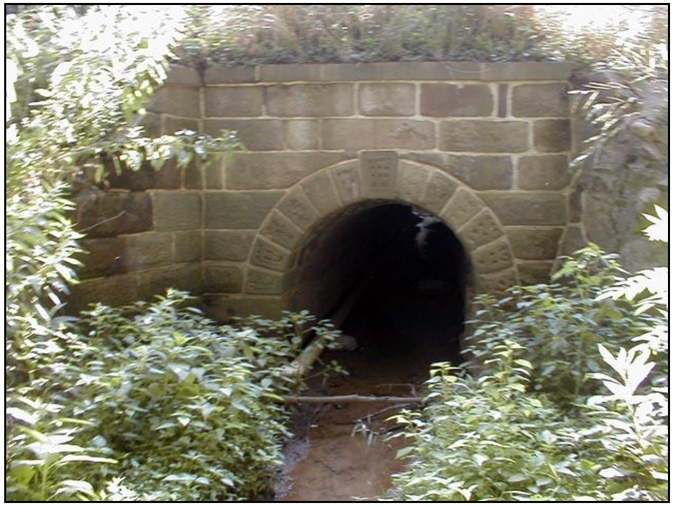
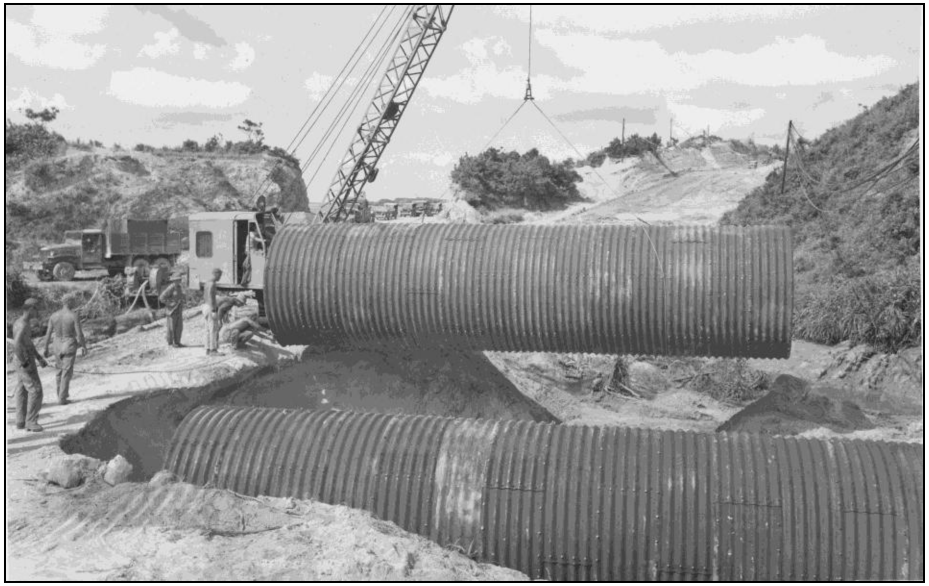
Compacting Culvert Inverts



Above: Prior to the 1930s most culverts were constructed of masonry, like this one

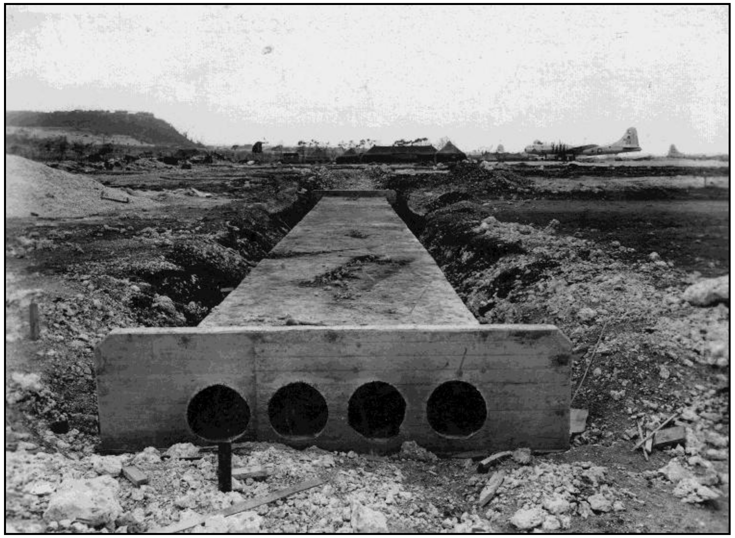
Below: Corrugated steel culverts were introduced in 1896. Segmented galvanized circular steel culverts (shown below) began to dominate practice in the 1930s

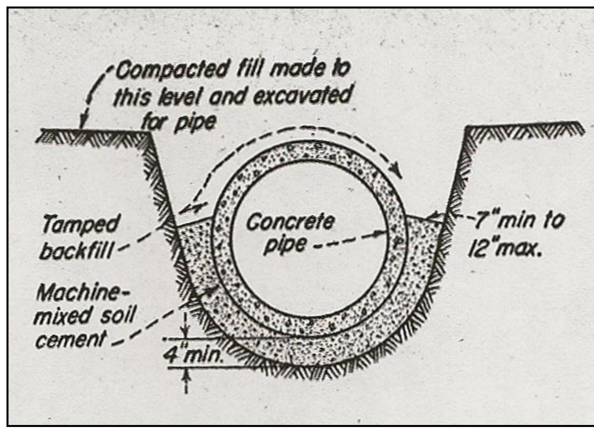


Little or no attempt was made in the early days to mechanically compact beneath the lower hemisphere of the circular culverts

- **The lack of compaction** beneath the lower hemisphere of the circular culverts led to numerous hydraulic piping failures, especially with cohesionless backfill.

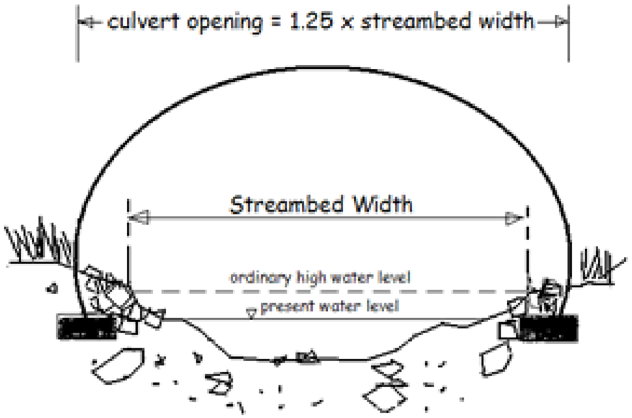
Early Solutions – 1940s





- **In the 1940s the problem was often solved by employing rectangular concrete footings, concrete boxes, slush grouting, and placing soil-cement backfill.**

Creative Solutions



Correctly installed open-bottom arch culvert with footings

Above left: Clear spanning the channel with parabolic shell on strip footings

Middle: mechanical compaction can be accomplished next to rectangular culverts

Lower left: Tamping well-graded backfill in thin lifts using Whackers

Upper right: Infilling the culvert hemispheres with crushed rock (OK for low head applications)

Parabolic Culverts

Parabolic culverts are manufactured in CMP, aluminum, and HDPE. The difficulty in compacting lower hemisphere backfill depends on their curvature, as seen in the upper left versus upper right images.

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Part 9

GROUND DEFORMATIONS TYPICAL of COMPACTED FILL

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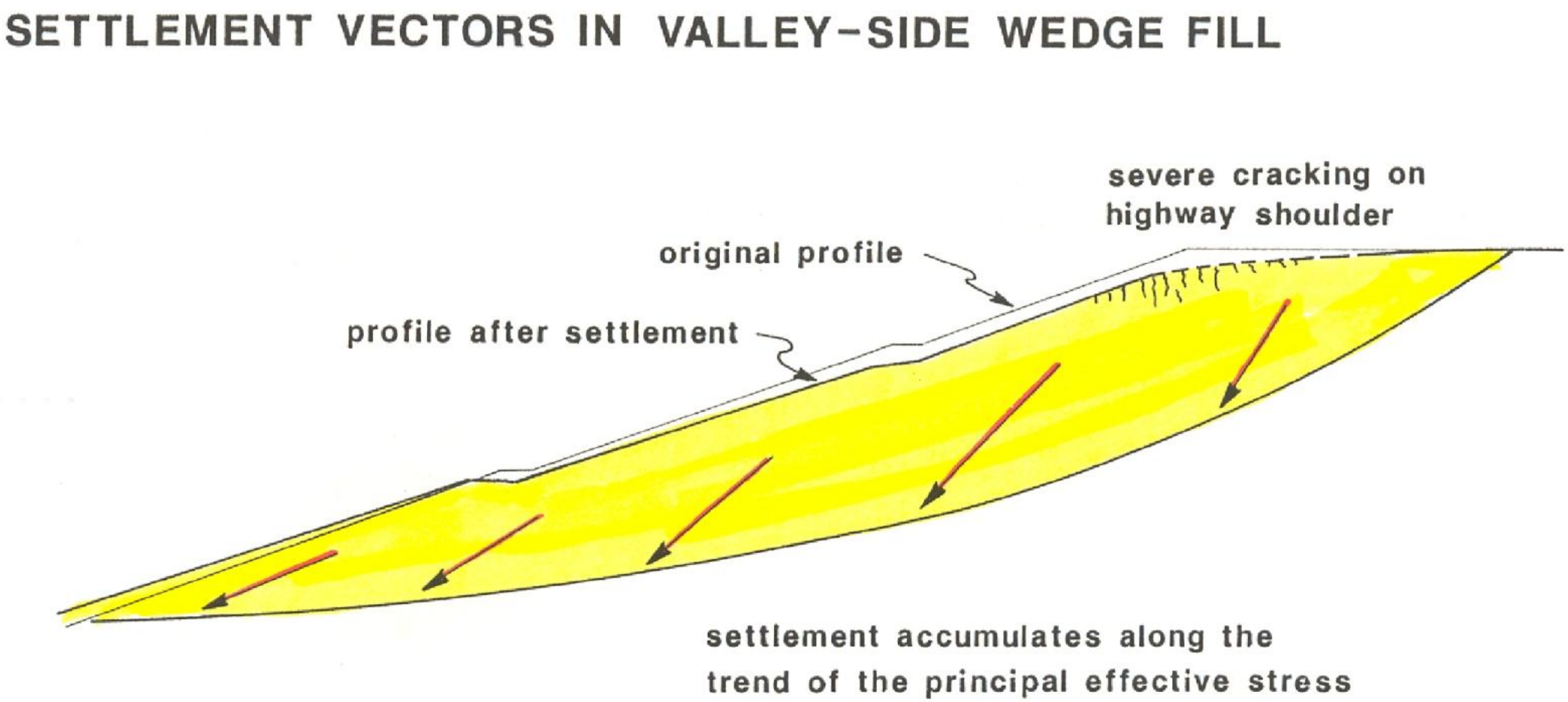
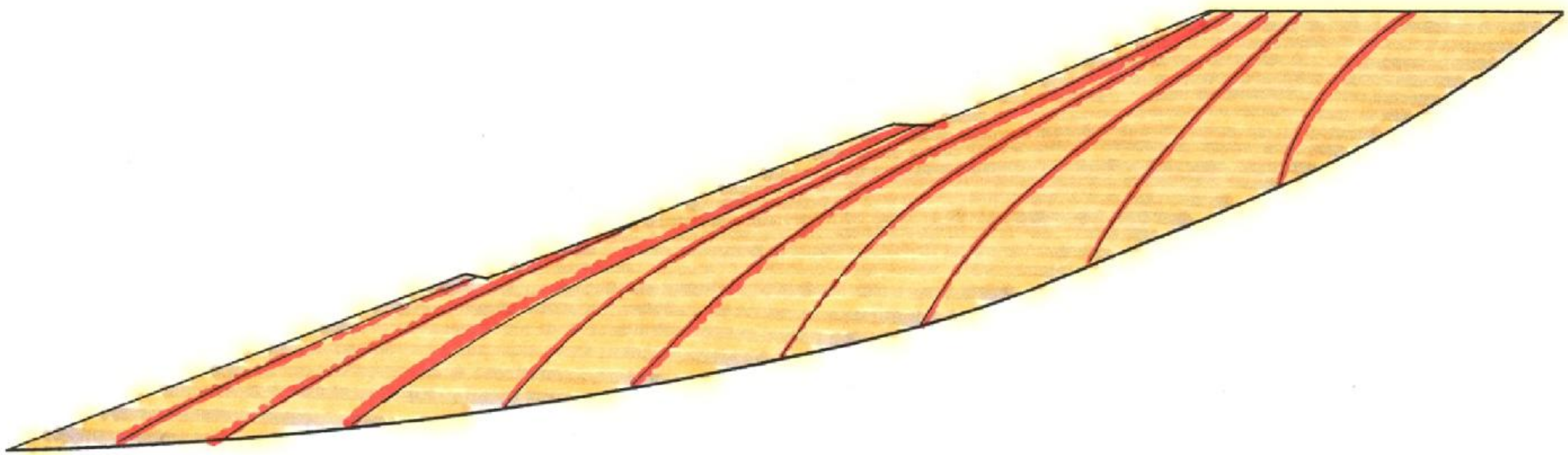
SLIVER FILLS



- **Sliver fills are prone to differential settlement with a significant horizontal component of movement (from Rogers, 1992).**

LAYERED SLIVER FILL

PRINCIPAL EFFECTIVE STRESS DISTRIBUTION
IN A VALLEY-SIDE 'SLIVER FILL'



- **Layering of cohesive and noncohesive soils can exacerbate settlement through more severely inclined effective stress trajectories. Settlement follows lines of maximum principal stress (shown in red)**

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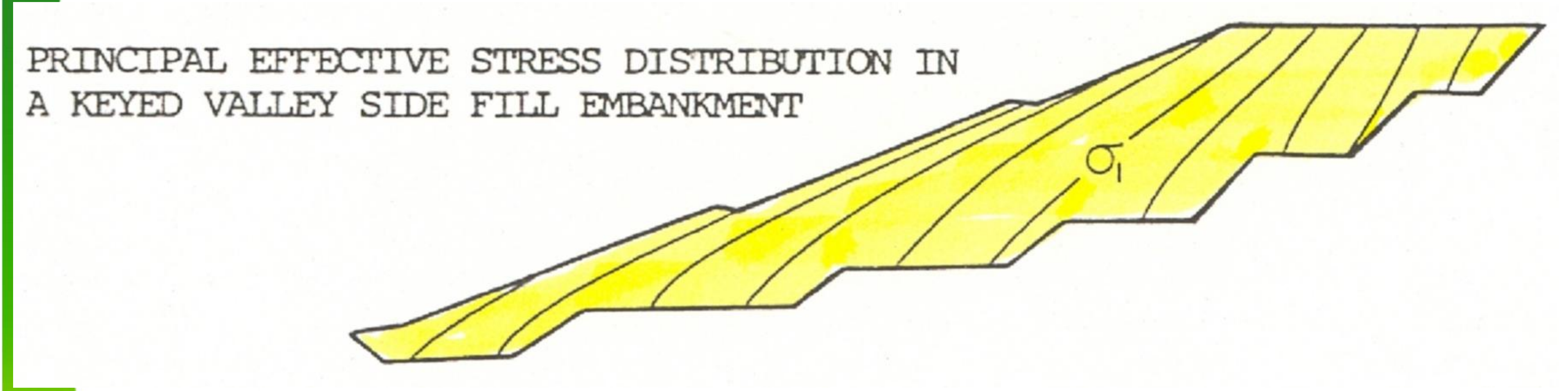
KEYED FILLS



- **Keyed fills tend to have less severely inclined principal stress trajectories, so differential settlement and horizontal component of settlement are reduced (from Rogers, 1992).**

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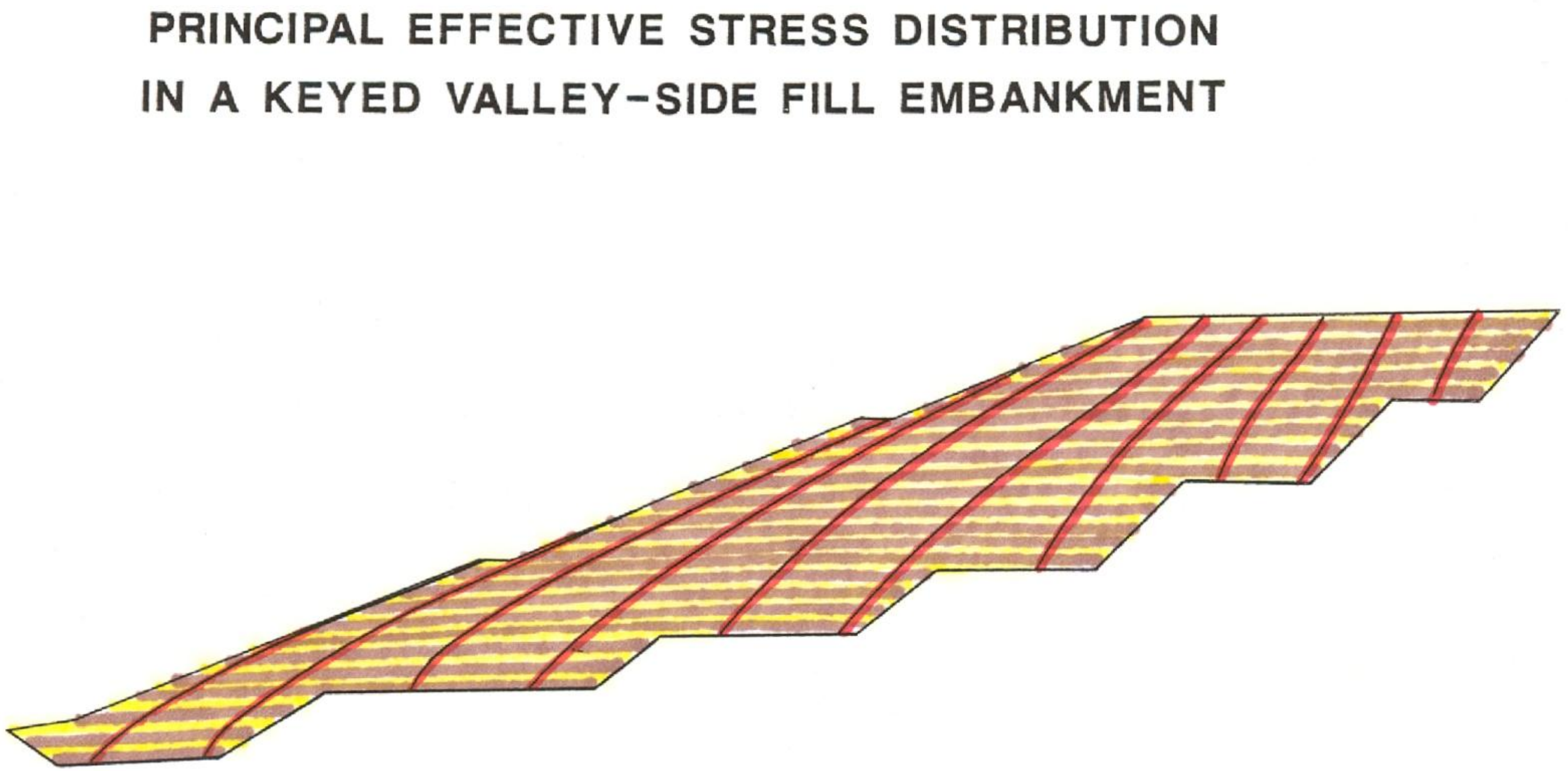
LAYERED KEYED FILL

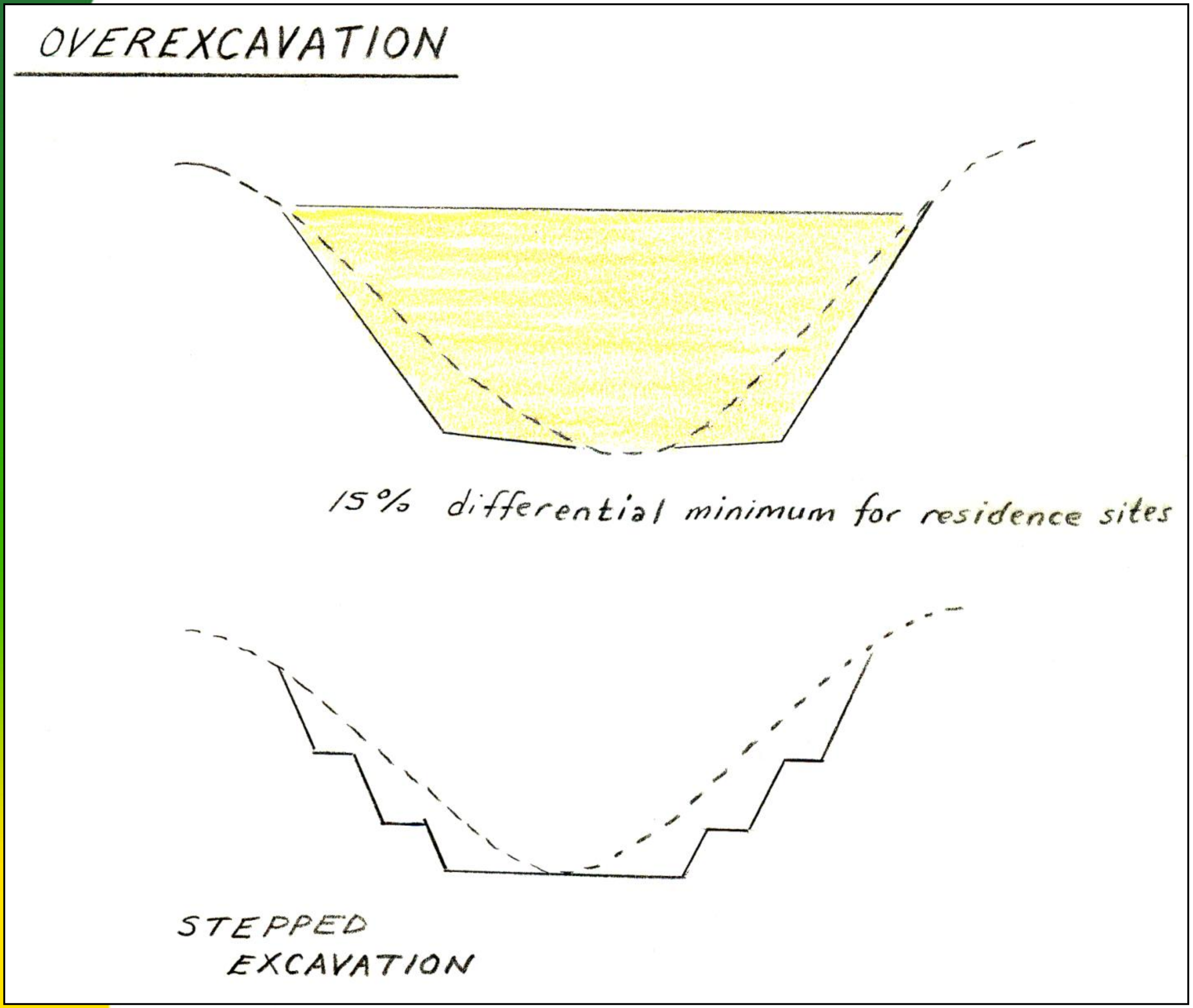


- **Layering of cohesive and noncohesive soils can exacerbate settlement through more severely inclined effective stress trajectories. Settlement follows lines of maximum principal stress (shown in red)**

MASS GRADING

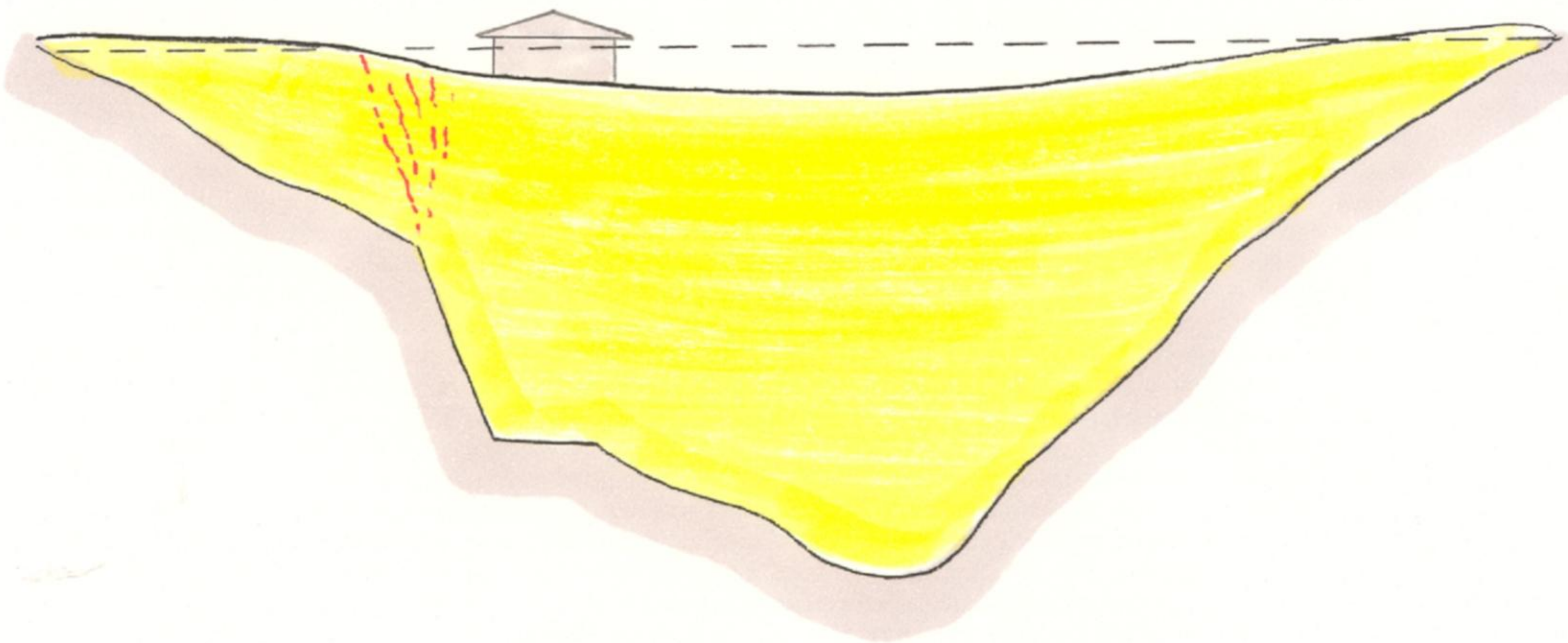
- **Mass grading is a term used to describe earthwork that has been engineered to support structures, water, or highways.**

CANYON CLEANOUTS



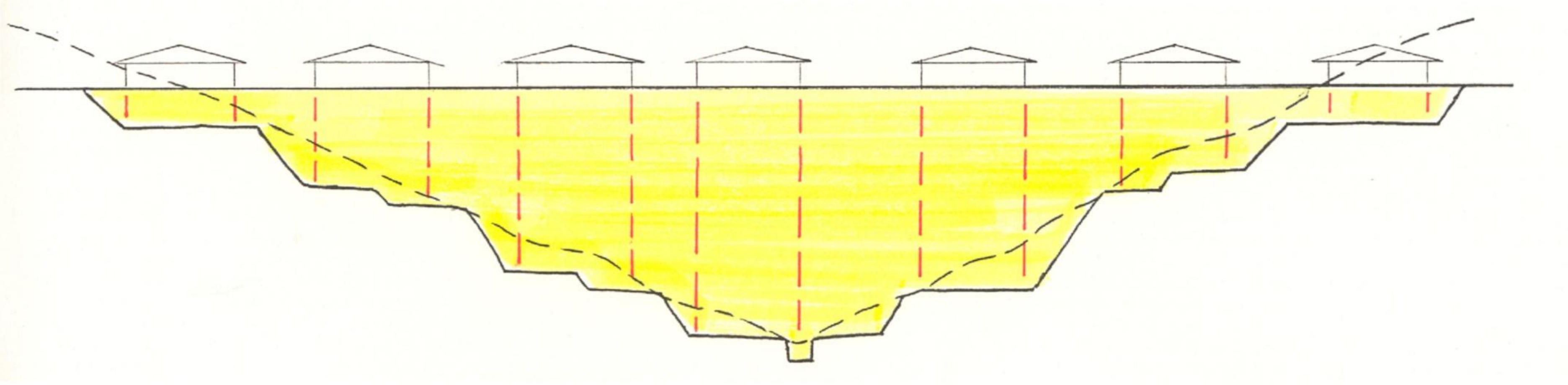
- **Canyon cleanouts or valley fills must be keyed and benched into adjacent slopes**
- **Fill thicknesses >15% differential and more than 30 feet deep should be avoided beneath structures, if possible**

UMR



- Unusually high benches in canyon fills can lead to **differential settlement and lot tilt**, as sketched above.
- This is especially problematic in earth dam embankments because tensile zones are created, which are subject to leakage and possible piping.

Benching beneath lots



- **Overexcavation benches** should be graded to avoid excessive differential fill thickness beneath the footprint of proposed structures to lessen lot tilt.

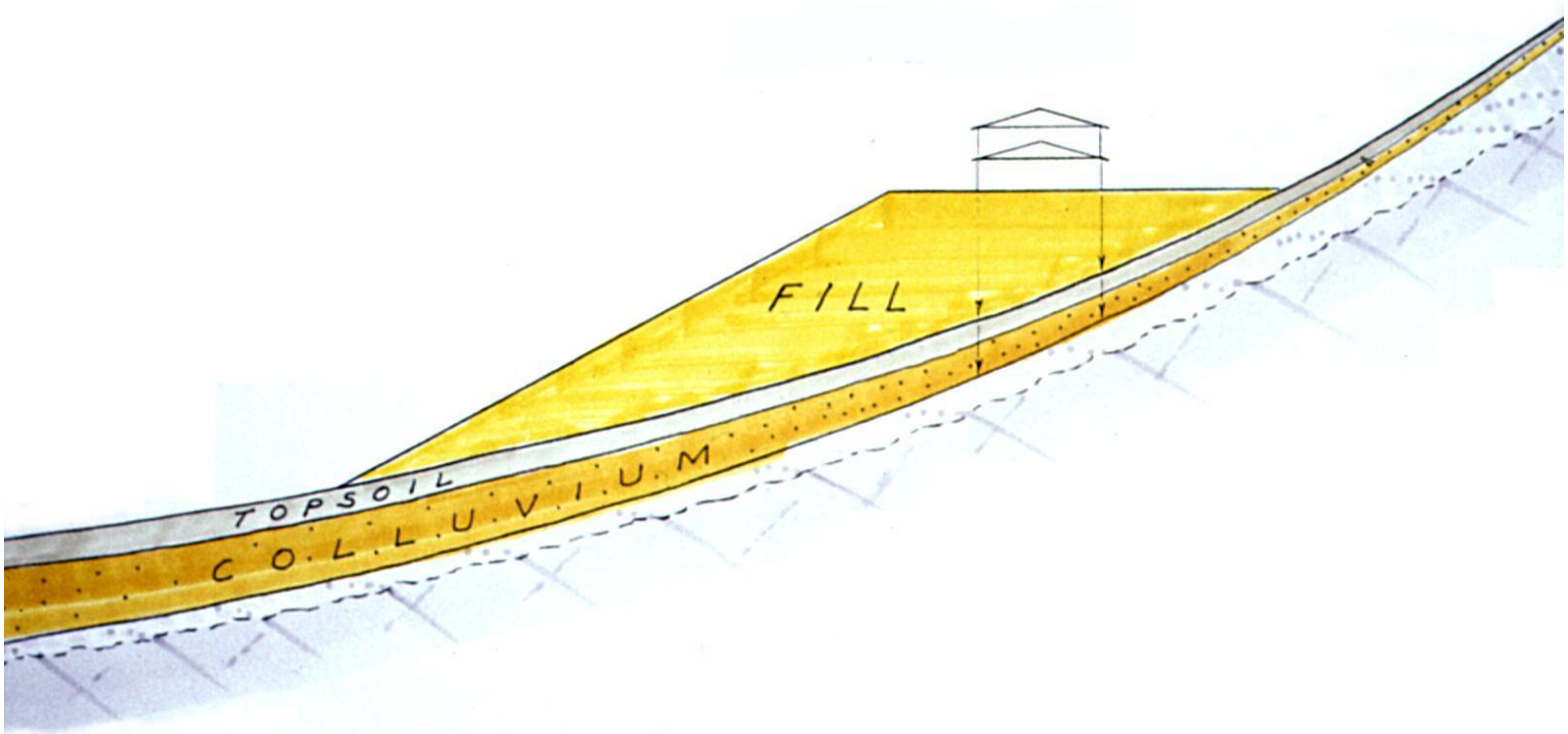
UMR

CUT-FILL TRANSITIONS

- **Differential settlement is almost unavoidable at severe cut-fill transitions, such as the one shown here. Such concentrated movement can sever buried utilities.**

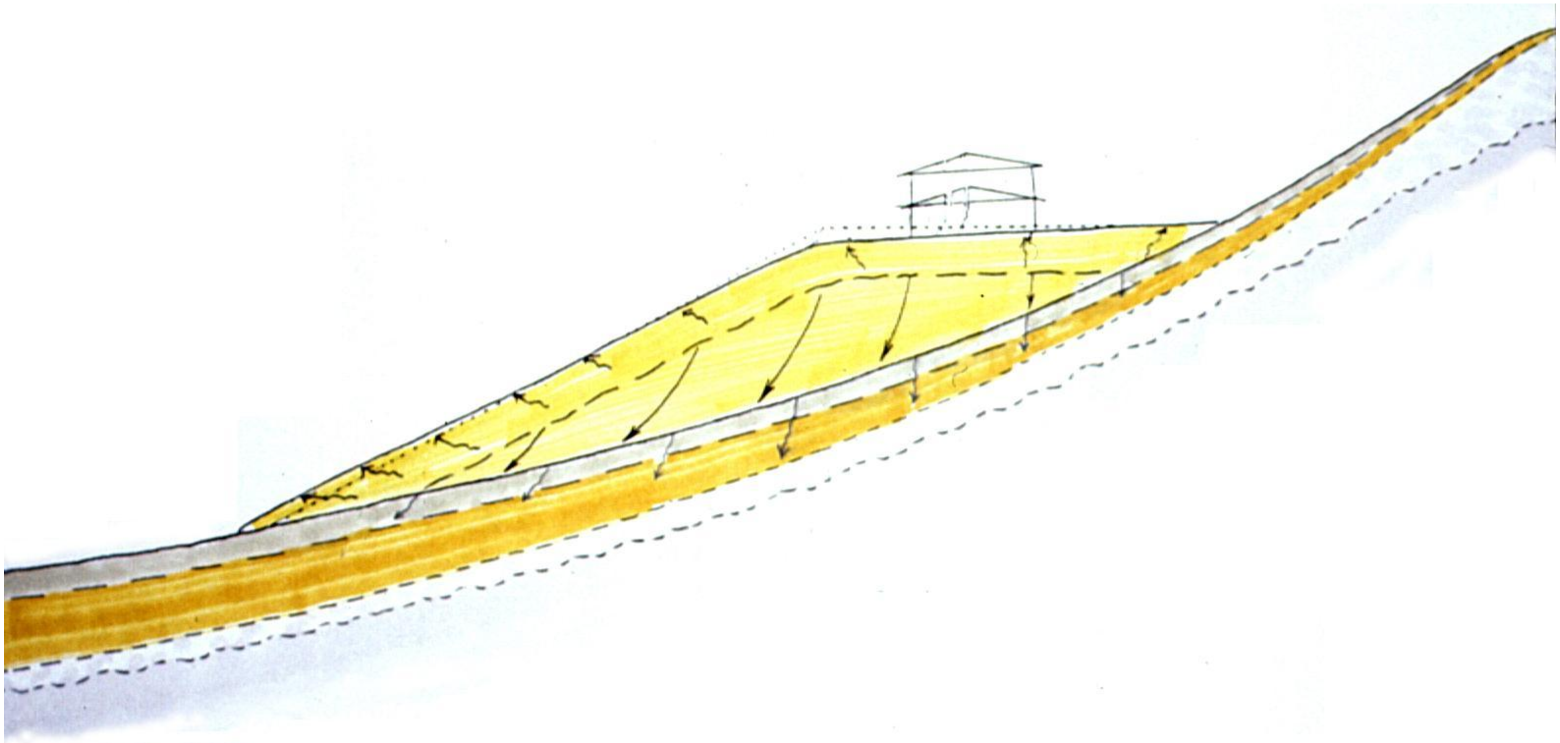
UMR

LONG TERM SETTLEMENT OF A SLIVER FILL



- **The fill and the structure create a surcharge on underlying topsoil and colluvium, which may be normally consolidated or underconsolidated**

SOURCES OF SETTLEMENT AND HEAVE



- **Sketch illustrating expected vectors of motion for near-surface heave *and* long-term settlement, after the soils become soaked. This may take several decades.**
- **The interpretation of inclinometer records from such sites can be exceedingly difficult and tedious.**

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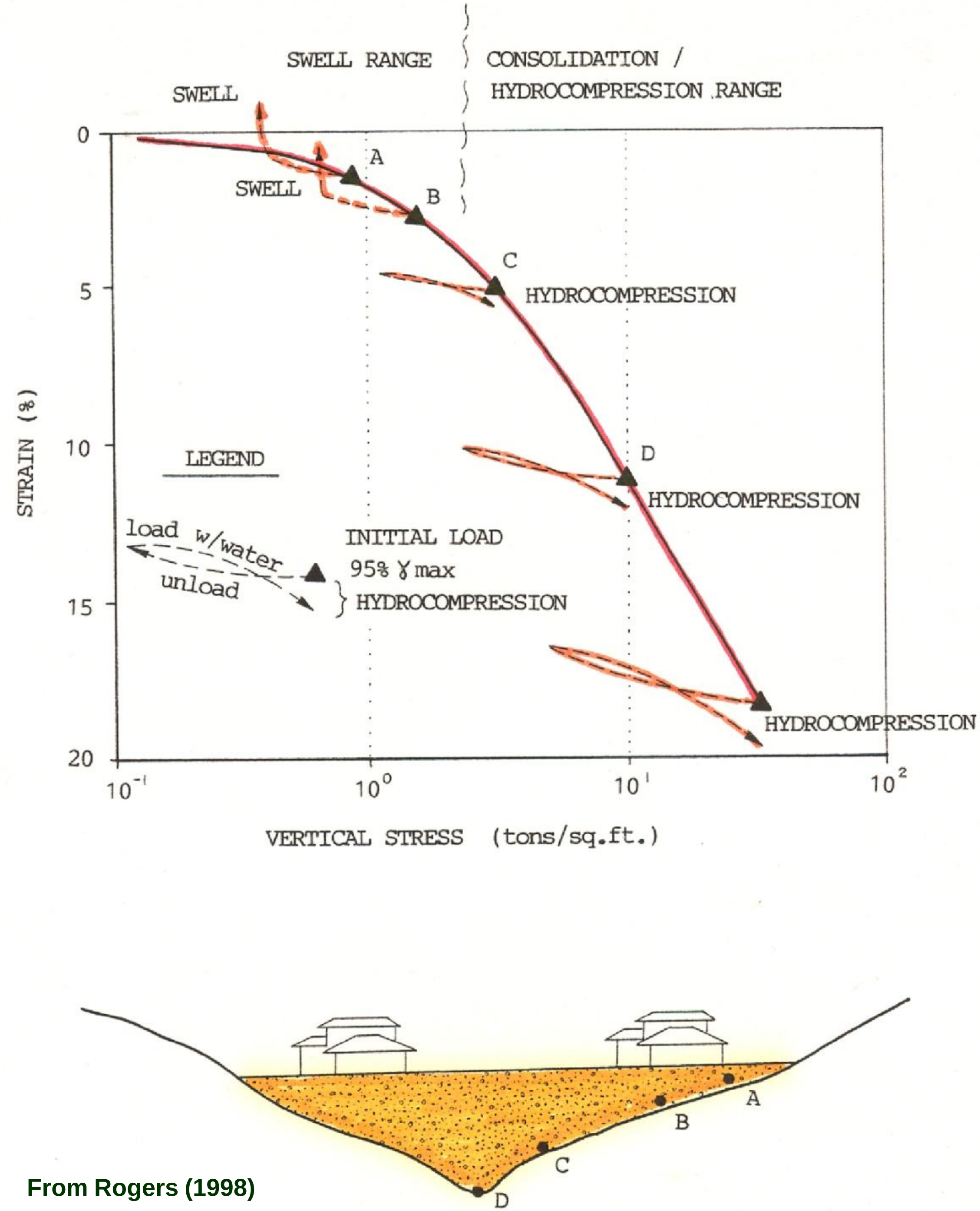
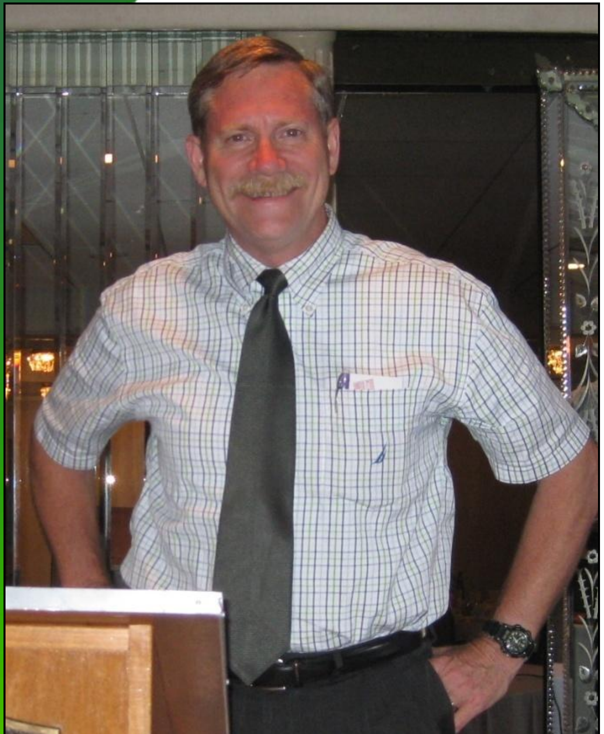


From Rogers (1998)

- **Hydrocompression** and **swell** can occur simultaneously in silty sandy mixtures containing expansive soils
- **This combination can cause excessive lot tilt because shallow fills will tend to heave while deeper portions will settle more than predicted with 1D consolidation analyses**
- **Note that overall settlement is *not proportional* to fill thickness!**

About the Presenter



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- Professor Rogers owned engineering consulting firms in Los Angeles and San Francisco and a general engineering contracting firm prior to entering academia.
- He served as Chair of the Building Codes Committee of the Association of Environmental & Engineering Geologists between 1990-97 and was AEG's representative to the International Conference of Building Officials (ICBO) during development of the 1991, 1994 and 1997 UBC's, and the 2000 IBC.
- Since 1984 he has taught short courses on grading and excavation codes for the International Conference of Building Officials in CA, OR, WA, HI, and Taiwan, as well as the University of Wisconsin, University of California, the Association of Bay Area Governments, and the City of Los Angeles. He was on the CE faculty at U.C. Berkeley between 1994-2001.