Development of Guidelines for Cuts in Loess Soils

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7. Author(s)
Dr. Jerry D. Higgins
Dr. Richard J. Fragaszy
Mr. Lawrence D. Beard

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Washington State University
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16. Abstract

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DEVELOPMENT OF GUIDELINES FOR CUTS IN LOESS SOILS

(PHASE I)

by
Dr. Jerry D.Higgins, Principal Investigator
Dr. Richard J. Fragaszy, Co-investigator
Mr. Lawrence D. Beard, Research Assistant

Washington State Transportation Center
Department of Civil & Environmental Engineering
Washington State University
Pullman, WA 99164-3001

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ABSTRACT

The first phase of a three-phase research investigation of cut slope design criteria for southeastern Washington loess has been completed. A literature review of engineering properties of loess from other locales and design criteria applied by various state transportation departments was conducted. Also, a preliminary field investigation was made to collect representative soil samples and record failure mechanisms. Past research has revealed that proper drainage control in combination with water content and gradational characteristics are the primary factors influencing cut slope performance in loessial soils. Analysis of 40 soil samples collected during the field study demonstrate a close similarity between southeastern Washington loess and deposits from the central United States. Although physical properties are similar, differing climates produce a disparity in failure mechanisms between midwestern and southeastern Washington loessial deposits.

SUMMARY

The performance of cut slopes in loessial soils is primarily influenced by water content and grain size distribution, provided adequate drainage is supplied. Early research conducted by Holtz and Gibbs (15) produced the gradational boundaries subdividing loessial deposits into sandy, silty, and clayey loess. The "critical water content" concept developed by Kane (17) explains the relationship between water content and shear strength in loess.

The Missouri State Highway Department (MSHD) (25) utilized the work of Holtz and Gibbs and that of Kane to develop the most up to date cut slope design criteria for loessial soils presently available. The MSHD design approach calls for vertical cuts when loessial soils fall within the silty loess gradational boundaries and exhibits water contents below critical (∿17%). Loess deposits not meeting the gradational or moisture requirements are flattened to 2.5:1 (H:V) or less.

Investigations conducted by the Tennessee Department of Transportation (TDOT) (30,31) produced useful design criteria, particularly with reference to erosion control. The primary erosion prevention methods employed by TDOT is construction of a drainage ditch 10-15 ft. behind the top of a cut slope, with side ditches constructed when needed.

A preliminary field investigation was conducted in an effort to determine the basic index properties and primary failure mechanisms of southeastern Washington loess. Analysis of 40 soil samples revealed a definite similarity in index properties between Washington and midwestern

loessial deposits. Conversely, analysis of existing failures in Washington loess revealed differences in failure mechanisms between deposits, primarily due to variations in climatic conditions. Due to lower precipitation in eastern Washington than in the central United States, failure mechanisms relating to high water contents, such as ice lens formation and truncated water tables, were absent. In Washington the majority of failures in silty loess were found to be due to a lack of erosion control. Failures in clayey loess were primarily caused by shallow downslope movements of saturated, thawed soil over frozen ground with oversteepened slopes aggrevating the situation.

CONCLUSIONS

Preliminary analysis indicates that the index properties of southeastern Washington loess are similar to those of midwestern loess. The range in gradation was found to be essentially the same as for Missouri River valley loess. The laboratory testing results suggest some trends in index properties for southeastern Washington loess. These are: 1) a decrease in mean grain size from west to east which is reflected in a decrease in percentage sand and an increase in clay and water content; 2) constituent percentages of sand, silt and clay remain relatively constant from north to south. The grain size analyses demonstrate the fact that the formation boundaries based on pedological classification (Palouse, Walla Walla, Ritzville, and Nez Perce loess) originally proposed by Eske (8) have little or no significance in defining engineering behavior.

Although when applicable, near vertical cut slopes are the most stable, definite design criteria must be met. In order to employ a vertical cut, gradation analyses must indicate that the soil falls within the zone defined as silty loess by Holtz and Gibbs (15), as well as have a natural water content that will never exceed critical (as defined in the text).

When vertical cuts cannot be utilized, flattened slopes should be cut no steeper than 2.5:1. Although 2:1 is sufficiently flat with respect to deep-seated slope stability in most cases, the ability of the slope to maintain a vegetative cover is greatly increased when flattened to 2.5:1.

The majority of slope degradation in road cuts through southeastern Washington loess were due to two problems. Within the portion of the deposit classified as silty loess, inadequate erosion control was the primary cause of failure or deterioration. In the eastern extreme of the study area, consisting of clayey loess, oversteepened cuts have resulted in severe loss of vegetative cover on many slopes due to shallow slides or flows. The loss of vegetative cover has resulted in gulley erosion of the slopes. Thus, seemingly minor design elements play a major role in the performance of a cut slope.

The keystone of successful erosion control is to provide adequate drainage above the cut. This is usually accomplished by constructing a drainage ditch 10-15 ft. behind the top of the cut, preferably before the cut is opened. Due to the highly erosive nature of loess, erosion control within the drainage ditch requires a minimum of heavy seeding. Synthetic liners or even pavement may be necessary at even moderate gradients. In most instances where long lateral cuts are employed, side ditches must be constructed to convey excess runoff away from the slope. Side ditches are generally steeper than lateral drainage ditches (above the crest of the cut) and will usually require a minimum of a graded gravel filter blanket.

When flattened cuts are utilized, slope protection must be initiated immediately following construction. Placement of a heavy straw mulch cover or synthetic materials immediately after seeding should be effective. In order to maintain a heavy vegetative cover, slopes should be fertilized periodically.

Toe drainage along a cut should consist of a conventional ditch; however, it should be placed away from the base of the slope. This will prevent saturation of the toe or damage from ditch cleaning operation, i.e., undercutting of toe.

RECOMMENDATIONS FOR FUTURE RESEARCH

Although much has already been learned about the engineering properties of southeastern Washington loess and loess in general, additional research is still needed. The long term objectives of the following recommendations are to enhance the design for all slope cuts whether they are very high cuts that may require a slope analysis or low routine cuts. The following areas are considered to be the highest priority.

1. Continue laboratory testing of samples already collected, also collect and test samples from locations previously omitted. Continued analysis is needed to adequately define trends in engineering and index properties with location.
2. Evaluate different techniques for obtaining undisturbed samples with emphasis on reduction of compressional effects in high water content areas. This is especially important since WSDOT collects loess samples by pushing Shelby tubes.
3. Evaluate available in-situ strength testing methods including pressure meter, Dutch cone and Iowa borehole shear tests. Due to sampling difficulties, in-situ testing may be a more economical and/or accurate method of obtaining strength data.
4. Establish a field performance evaluation of cut slopes to experiment with the design criteria suggested in this report. A number of test sections, constructed with a wide range in slope (perhaps between 0.5:1 and 3.0:1) and drainage systems are needed.

By monitoring slope and drainage system performance, it should be possible to determine the cut slope angle necessary to maintain good vegetative cover as well as the most reliable and serviceable drainage system in relation to cost.

INTRODUCTION

Loess is a wind deposited soil composed primarily of silt sized particles. Major deposits of loess are located in China, Europe, and the United States. While the most extensive deposits in the United States are located in the midwest, a substantial portion of southeastern Washington is covered by loess.

The word "loess" is derived from the German word "lösen" which means to loosen or dissolve, and is descriptive of the structure associated with loessial soils. Loess is characterized by its loose structure which consists of silt and fine sand particles coated by a clay binder. This structure allows vertical or near vertical cuts exceeding 50 ft in height to perform exceptionally well, provided the water content remains low. Conversely, upon wetting loess becomes relatively unstable and slump failures can occur in slopes as flat as 2:1 (H:V). In addition to slope failures, excessive settlement of foundations upon wetting (termed hydroconsolidation) is a well known phenomenon in loessial soils.

When the structure of loess is considered, its adverse reaction to increased water content is easily understood. Due to the clay coating on the silt and sand particles there is little intergranular contact, particularly at low confining pressures. Thus most of the strength is attributable to the clay binder. At low water contents high negative pore pressures develop in the binder, producing high shear strength. As a result, loess has the ability to stand in vertical cuts and support large loads as a foundation material as long as it remains unsaturated. However, upon wetting, the negative pore pressures are eliminated which reduces effective stresses, and thus strength as water content within the clay fraction increases to near saturation.

In addition to loss of strength, settlement from wetting (hydroconsolidation) is a result of structure. As previously stated loess exhibits a loose structure, i.e., a high void ratio. Upon wetting, the reduction in shear strength allows the granular material to reorient, producing a denser soil with a substantially lower void ratio which results in large settlements. It was this tendency to consolidate, particularly with respect to earth dam foundations, that led to much of the original research on the physical properties of loessial soils performed by the Bureau of Reclamation in the early 1950s and 1960s (8,15).

The vast majority of research on the engineering characteristics of loess has been done in the midwestern and southern U.S., primarily Missouri, Iowa, Kansas, Tennessee, and Mississippi. It is not surprising that research in Washington has lagged behind the central United States. Only recently has highway construction and realignment in southeastern Washington necessitated slope cuts of such a height and lateral extent that design criteria specific to loessial soils is required.

The ultimate objective of this research is to determine whether current procedures used by the WSDOT for highway cuts in loess soils are adequate and, if not, to formulate new guidelines. The project is divided into a 3-phase approach. Phase 1 is a state-of-the-art review of the engineering properties of loess with emphasis on slope stability. Included is a survey of methods used in Washington and other states for design of loess slopes. Also, inspections of selected cuts within the state of

Washington were made. Upon conclusion of this review, it would be determined whether significant improvements can be made in the design procedures currently used in Washington. Phase 2 of the project would consist of evaluating additional cut slopes in Washington (both failed and unfailed) and identifying failure modes. The research would concentrate on the identification of environments and soil properties governing slope failure, and evaluation of the possibility of predicting failure mechanisms on a site specific basis. Phase 3 would include formulation and implementation of design guidelines and monitoring of test slopes.

This report represents the culmination of Phase 1. Contained within is:

1. A literature review of the physical properties which control performance of cut slopes in loess, a summary of index properties for loessial deposits within the United States, and a review of engineering practices employed by other states for cut slopes in loess.
2. Evaluation of the index properties of southeast Washington loess based on samples collected in the summer of 1984.
3. Preliminary evaluation of cut slope failures and associated failure mechanisms observed in southeastern Washington loess.
4. Preliminary design criteria based on methods employed by other state transportation departments in conjunction with cut slope stability problems observed in southeastern Washington.
5. Recommendations for future research based on present results.

The literature review was performed with the cooperation of the WSDOT librarian. The Geodex system was employed as well as bibliographies from previously obtained references. References found include research reports on the general index and engineering properties of loess, properties of specific deposits, and cut slope design criteria utilized by individual states. Also, letters were sent to various state transportation departments by WSDOT requesting information on present design practices in loess.

The field study had the twofold purpose: to obtain samples for analysis of index properties and to evaluate performance of existing highway cuts. A total of 67 bag samples were obtained from 46 locations. Discrete vertical sampling was performed at three sites with five to eight samples taken at each site. In addition to bag samples, eight Shelby tube samples from two sites were obtained by WSDOT personnel. Numerous slopes were inspected during the course of sample collection in an effort to determine primary failure modes and regional trends in the types of failures.

Laboratory testing on bag samples included grain-size analysis, Atterberg limits, specific gravity and natural water content. Tests were conducted on 40 representative samples. Based on this work, a comparison of southeastern Washington loess to deposits located in other states was performed. In addition, vertical trends in index properties and variation with location were examined.

LITERATURE REVIEW

Fundamental Properties of Loess

The first comprehensive study of the engineering and index properties of loess was conducted by Holtz and Gibbs (15). Although they were primarily interested in consolidation, basic laboratory tests including gradation, specific gravity, plasticity, and shear strength were performed on a large number of samples. Grain size characteristics revealed that the majority of samples (71%) fell within gradation limits arbitrarily defined as silty loess. Samples found to be finer than the boundaries established for silty loess were termed clayey loess (21%) while coarser samples were categorized as sandy loess (8%). A grain size distribution chart delineating these subdivisions is presented in Figure 1.

In addition, they conducted Atterberg limits tests and plotted the results on a plasticity chart. The plot exhibited a concentration of points with plasticity indexes ranging from 5 to 12 and liquid limits between 28 and 34. Examination of these data in conjunction with the gradation analysis reveals that the concentration was indicative of silty loess. Furthermore, a more poorly defined grouping of higher plasticity index and liquid limits was found to coincide with gradation curves in the clayey loess range. Thus, a useful relationship between gradation and plasticity was established.

Holtz and Gibbs found shear strength, as determined by triaxial testing, to vary considerably with water content and to a lesser extent with dry density. As would be expected, strength increased with decreasing

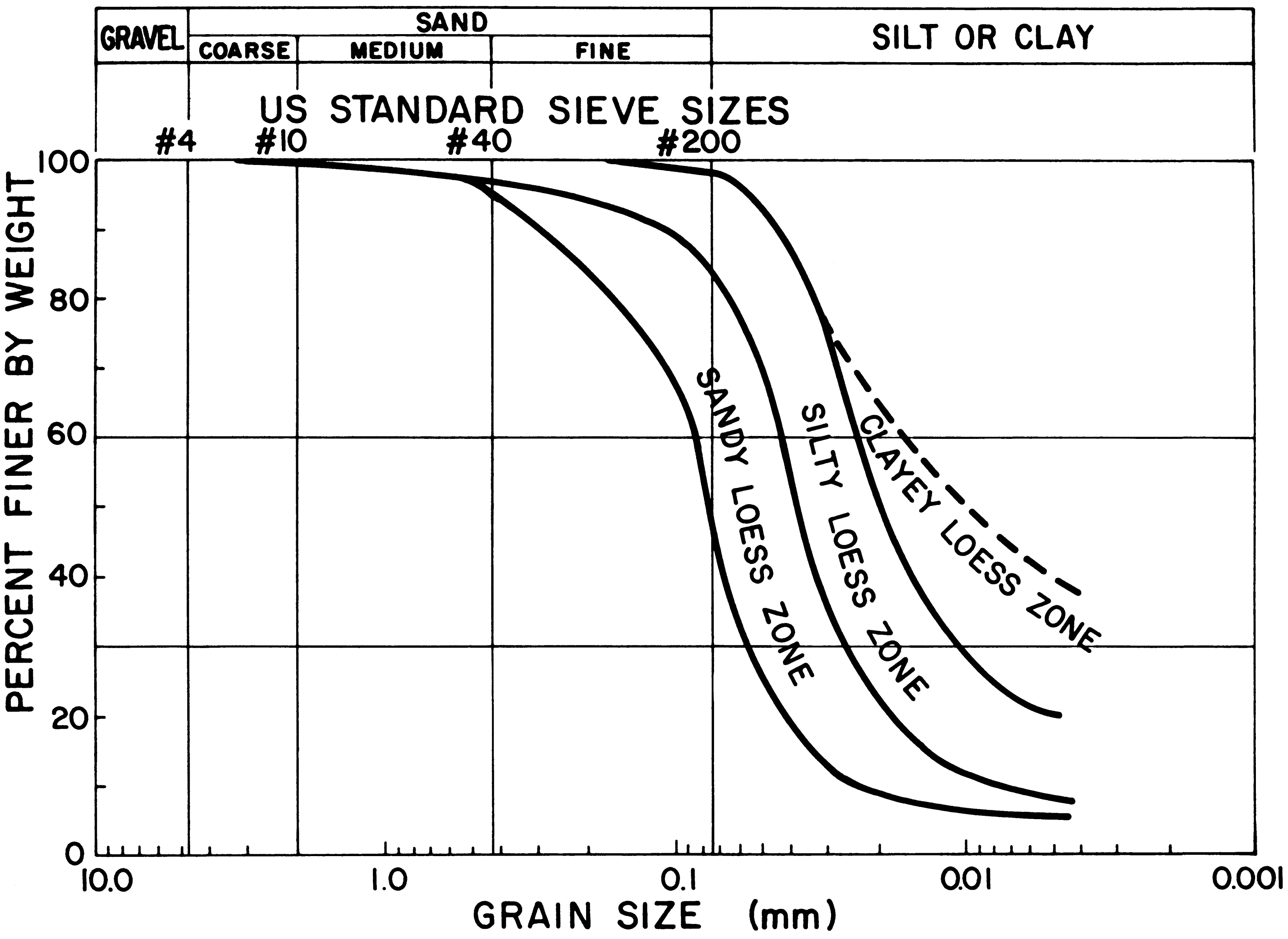

Figure 1. Range in grain size distribution for Missouri River Valley loess.

water content and increasing density. The angle of internal friction remained fairly constant, ranging from 30 to 34 degrees, while the cohesion intercept increased rapidly as water content decreased.

Holtz and Gibbs (15) refer to the strength parameters as effective, but it is unclear whether this is the case, particularly with respect to the unsaturated samples. In order to determine effective stresses during triaxial testing it is necessary to measure pore water pressures which can only be easily determined under saturated conditions. It would appear total rather than effective stress parameters were obtained with the cohesion intercepts due to negative pore pressure and therefore not indicative of true cohesion.

Although it was felt by Holtz and Gibbs (15) that strength was not affected substantially by the gradational subdivisions (sandy, silty, clayey loess), it is evident that this is not true at low water contents, when a total stress analysis is employed. Obviously, undrained cohesion will increase with increasing clay content for a given water content below saturation, resulting in higher strength. However, this effect is at least partially offset by the tendency of clayey loess to maintain a higher natural water content than silty or sandy loess (25).

Gibbs and Holland (9) expanded the data base of the original work by Holtz and Gibbs (15). Additional laboratory tests were incorporated into the report as well as plate load and pile driving tests. Results pertinent to strength properties remained essentially unchanged.

The relationship between water content and shear strength was more thoroughly explained by Kane (17) who presented what he termed the "critical water content" concept. Unconsolidated-undrained (UU) triaxial shear tests were conducted at various water contents on undisturbed samples obtained from a site near Iowa City, Iowa. In addition, tests to measure negative pore water pressures and volumetric variation with water content were performed.

It was found that above a given water content (critical water content) the clay binder was volumetrically stable. Below the critical water content the clay fraction shrinks as a result of desiccation. The critical water content may also be described as the water content at which the clay binder becomes saturated. This mechanism provides a reasonable explanation of the variation in strength with water content. Since the clay binder is essentially saturated once critical water content is reached, any additional water fills voids between particles and has little effect on effective stress levels until complete saturation is achieved. As water content decreases below critical, desiccation takes place which results in the development of negative pore water pressures in the clay binder. As the water content decreases, the negative pore pressure increases causing increased effective confining pressure and thus increased strength.

The applicability of the critical water content concept to specific field problems is questionable. The measurement of negative pore pressures is a difficult, time consuming procedure requiring special apparatus. Additionally, critical water content will vary with clay content, which tends to vary with location. If a relationship between percentage clay and critical water content can be established for a given loessial deposit, the concept may have practical applications.

Index Properties and Shear Strength of Loess

The index properties of loess have been determined for many locations in the central United States and Alaska. Before cut slope design criteria developed by other states can be applied locally, it is necessary to determine whether the index properties of the deposits for which the design criteria have been developed show a high degree of similarity to the properties of Washington loess. To this end, the index properties for various loessial deposits within the United States are summarized in the following paragraphs.

Clay Composition

Montmorillonite, or a combination of montmorillonite and illite are the dominant clay minerals for loess deposits in the central United States (2,4,9,12,20). The clay fraction of Alaskan loess is predominantly chlorite with minor amounts of illite and possibly kaolinite (7).

Caclium Carbonate

Calcite deposits in loess are generally found as discrete grains, root fillings, or nodules (9,15). In some cases a continuous layer or crust of calcite may form. This crust generally forms as the result of evaporation and has been observed on cut slopes in Mississippi (20).

When present in sufficient quantities calcite increases the dry strength of loess. However, due to the discontinuous nature of calcite accumulation, care must be taken when determining strength properties for a specific site. If test samples are obtained from a location containing a larger than average percentage of calcite, tests will indicate a strength higher than what actually exists for the site as a whole.

Gradation

Gradation characteristics from different locations are presented in Figures 2 through 7. In general, the range in grain size distribution falls within the bounds established by Holtz and Gibbs (15) with the exception of Alaskan loess which tends to be slightly coarser. The maximum grain size in loessial deposits examined within the continental United States is 2.00 mm (No. 10 sieve), while analysis on Alaskan loess exhibit an upper limit of 9.53 mm (3/8 in. sieve). Present theory is that the particles in Alaskan loess larger than 2.00 mm may be carbonate concretions formed after deposition of the loessial unit, although testing has not been performed to substantiate this hypothesis (32).

Plasticity

The results of Atterberg limits tests from various investigations are presented in Figure 8. Although a substantial degree of variability can be observed in the range of plasticity from location to location, the approximately linear relationship between liquid limit and plasticity index appears to be similar for all locations.

Shear Strength

Shear strength is the most important engineering property of any soil when considering slope stability. Unfortunately, shear strength is difficult to quantify for loessial soils when saturation is less than 100%. As previously mentioned, the angle of internal friction remains relatively constant, between 28 and 36 degrees, while the cohesion intercept varies inversely with water content.

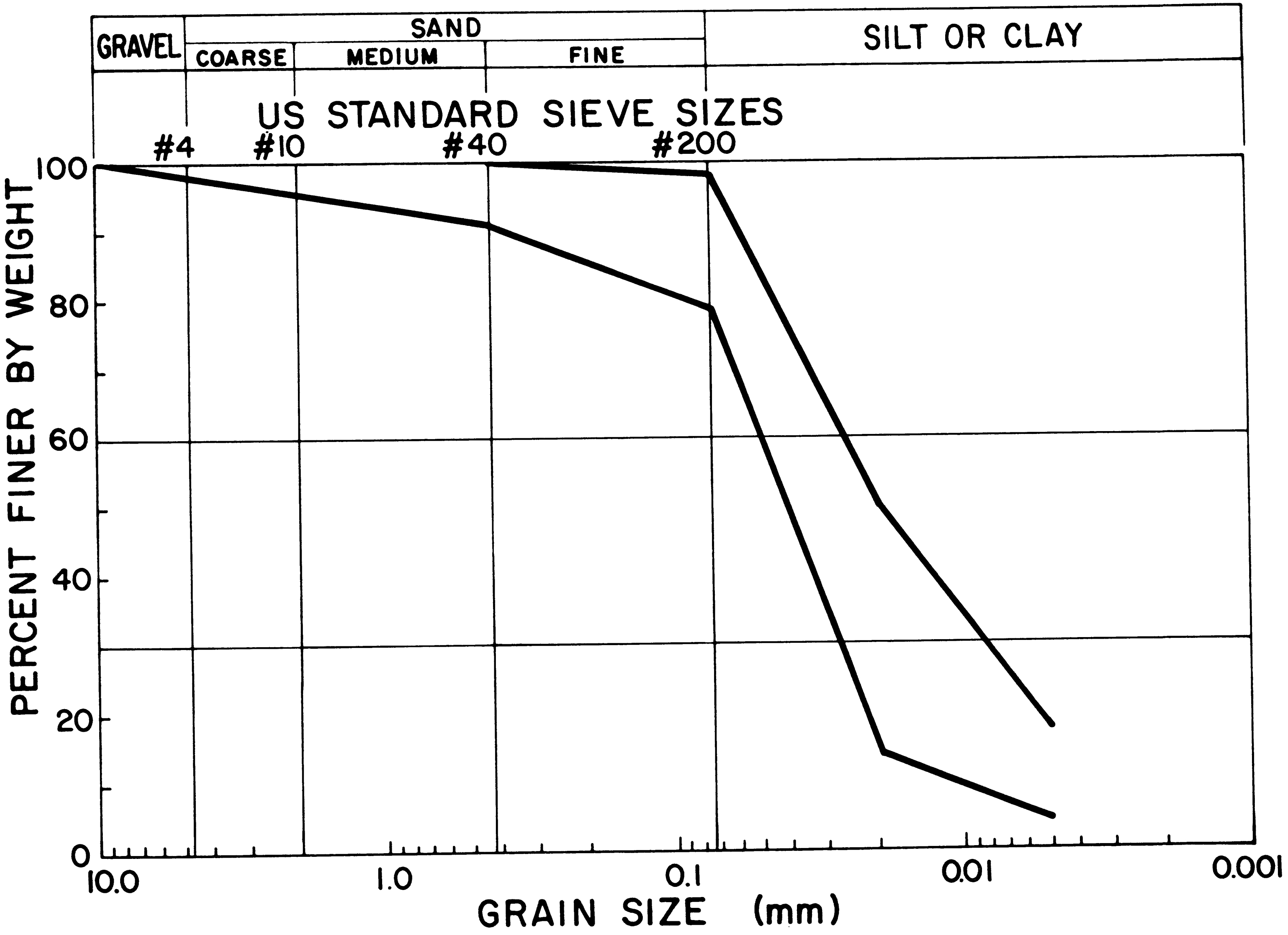

Figure 2. Range in grain size distribution for Alaska (27).

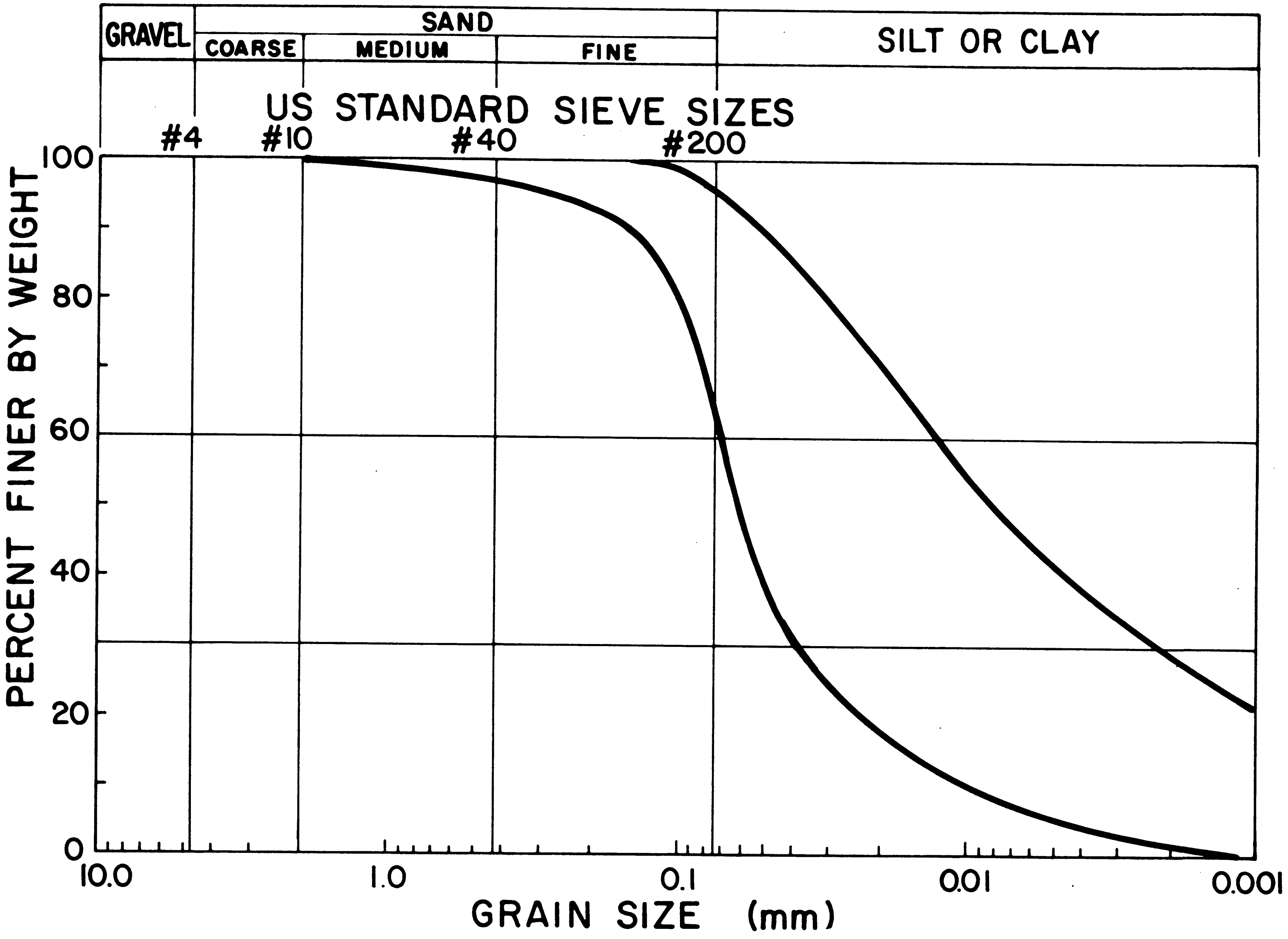

Figure 3. Range in grain size distribution for Kansas (2).

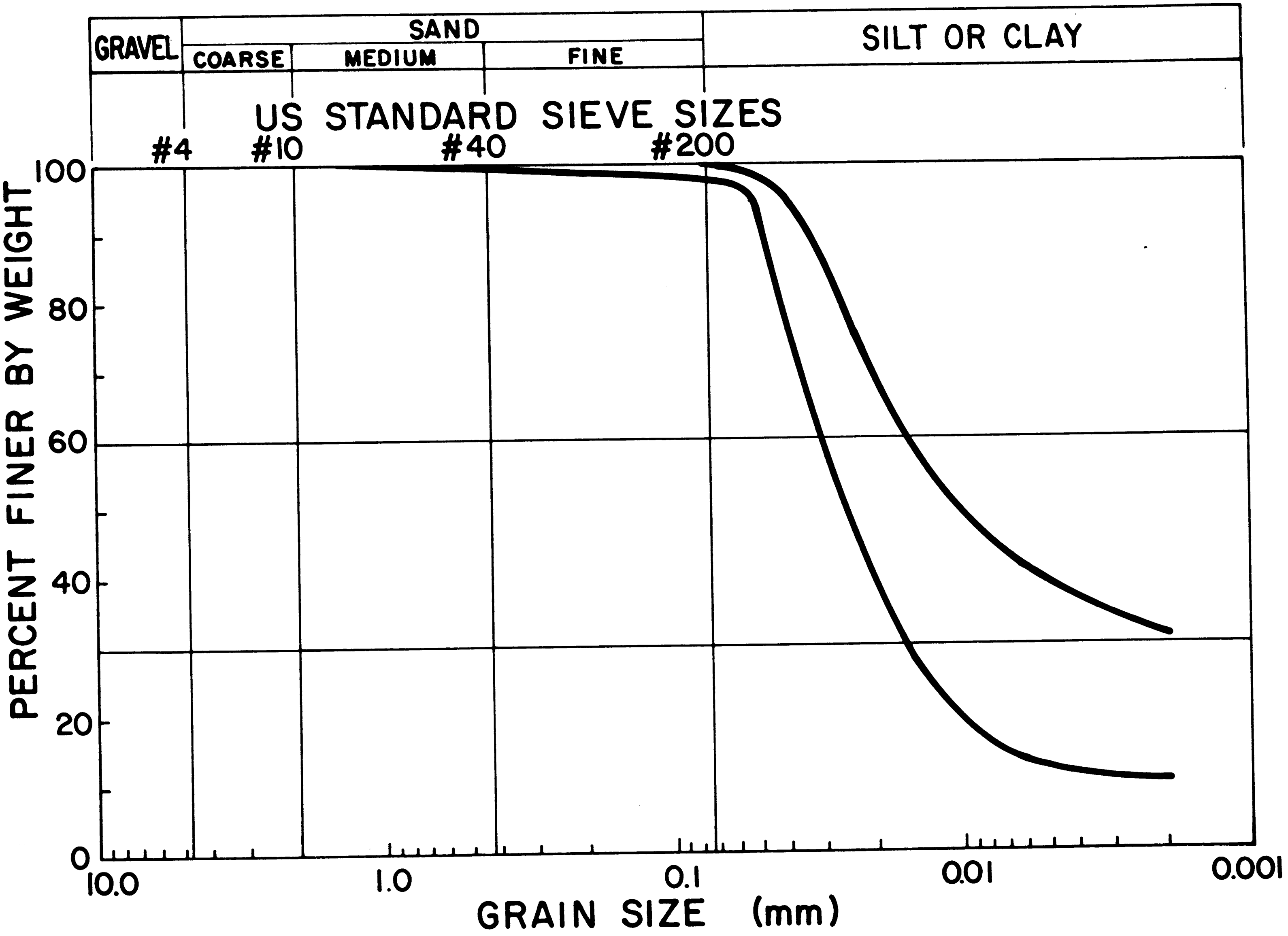

Figure 4. Range in grain size distribution for southwestern Iowa (6).

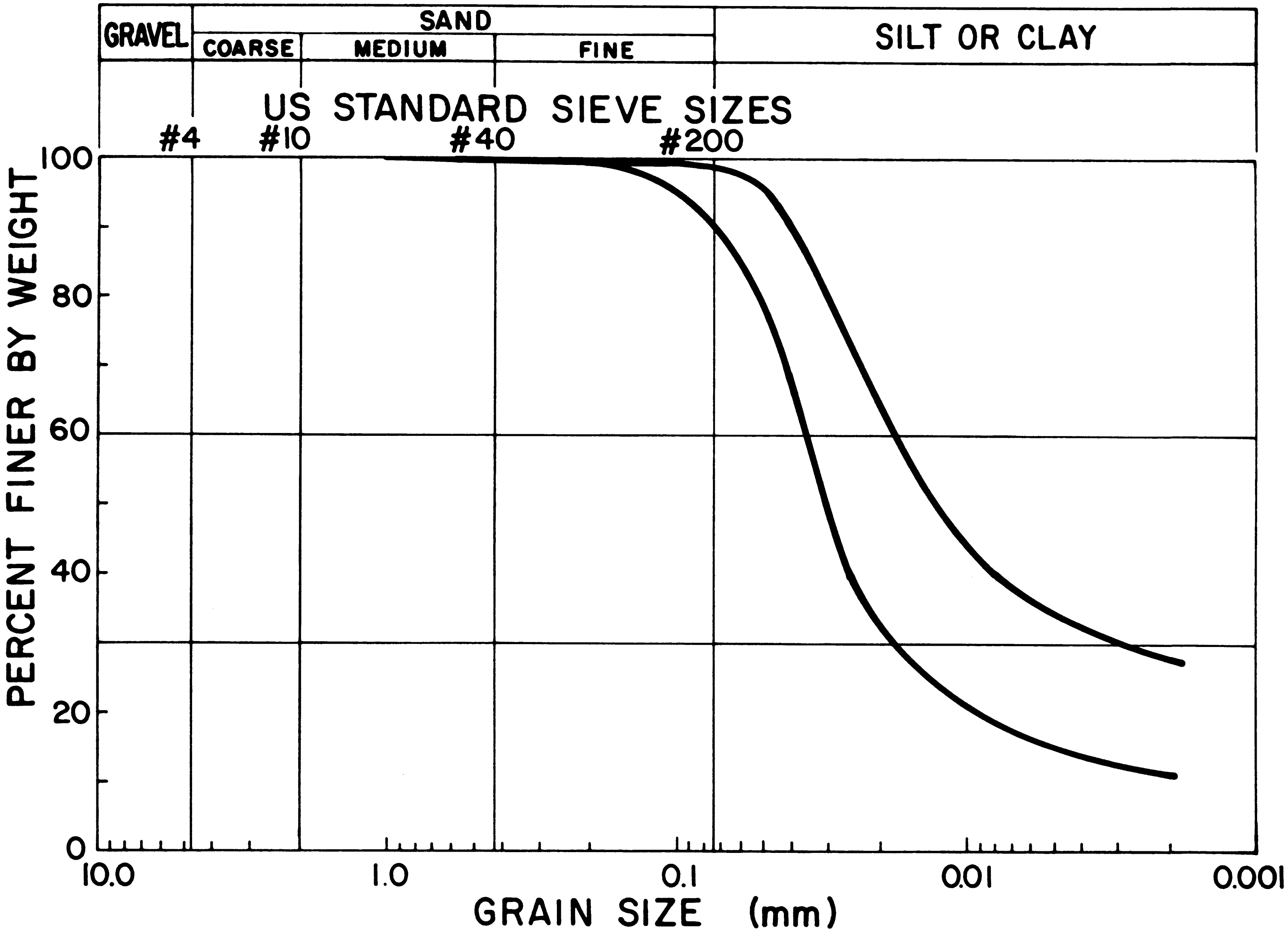

Figure 5. Range in grain size distribution for east-central Iowa (12).

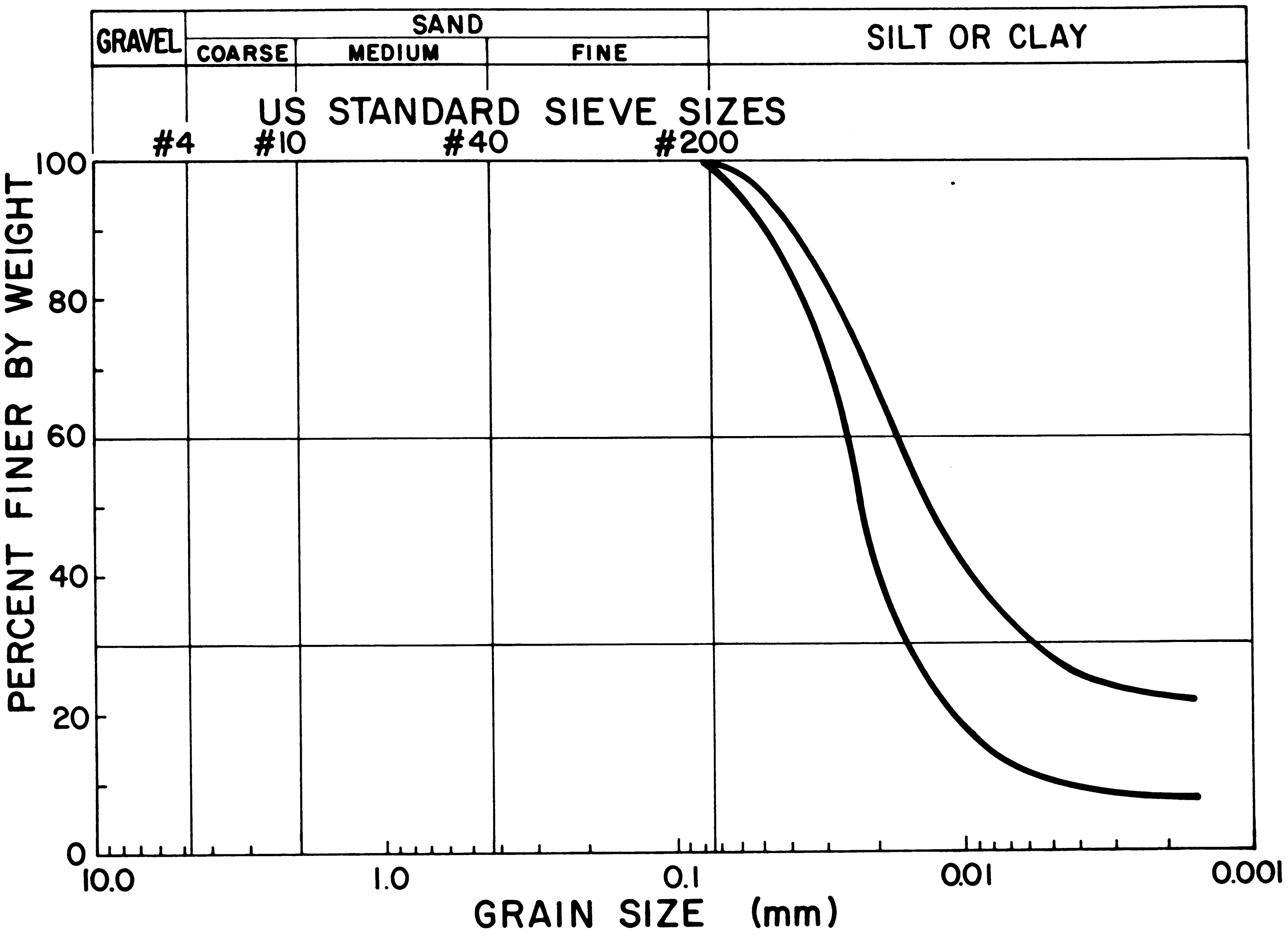

Figure 6. Range in grain size distribution for Mississippi (20).

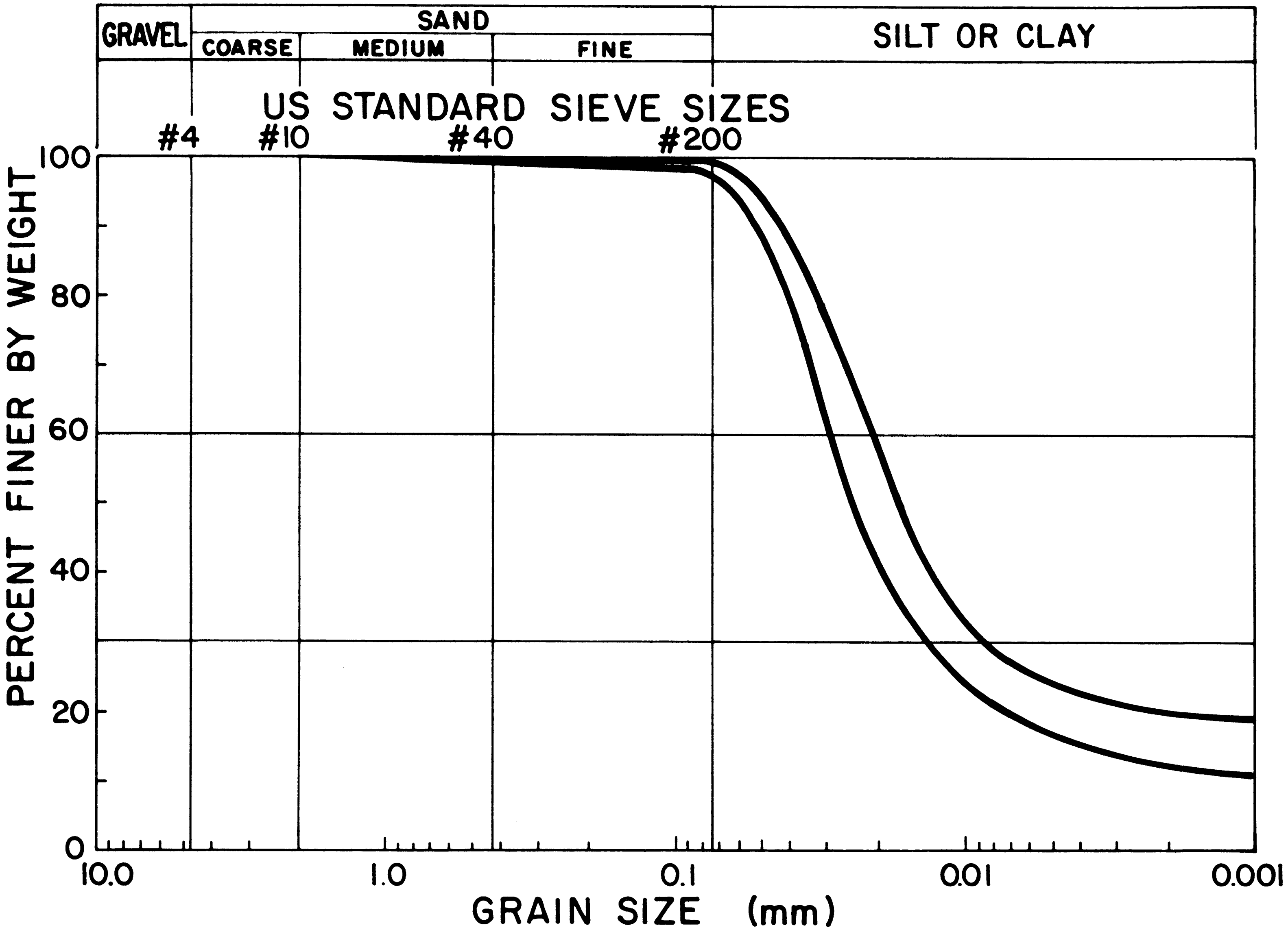

Figure 7. Range in grain size distribution for northeast Iowa (12).

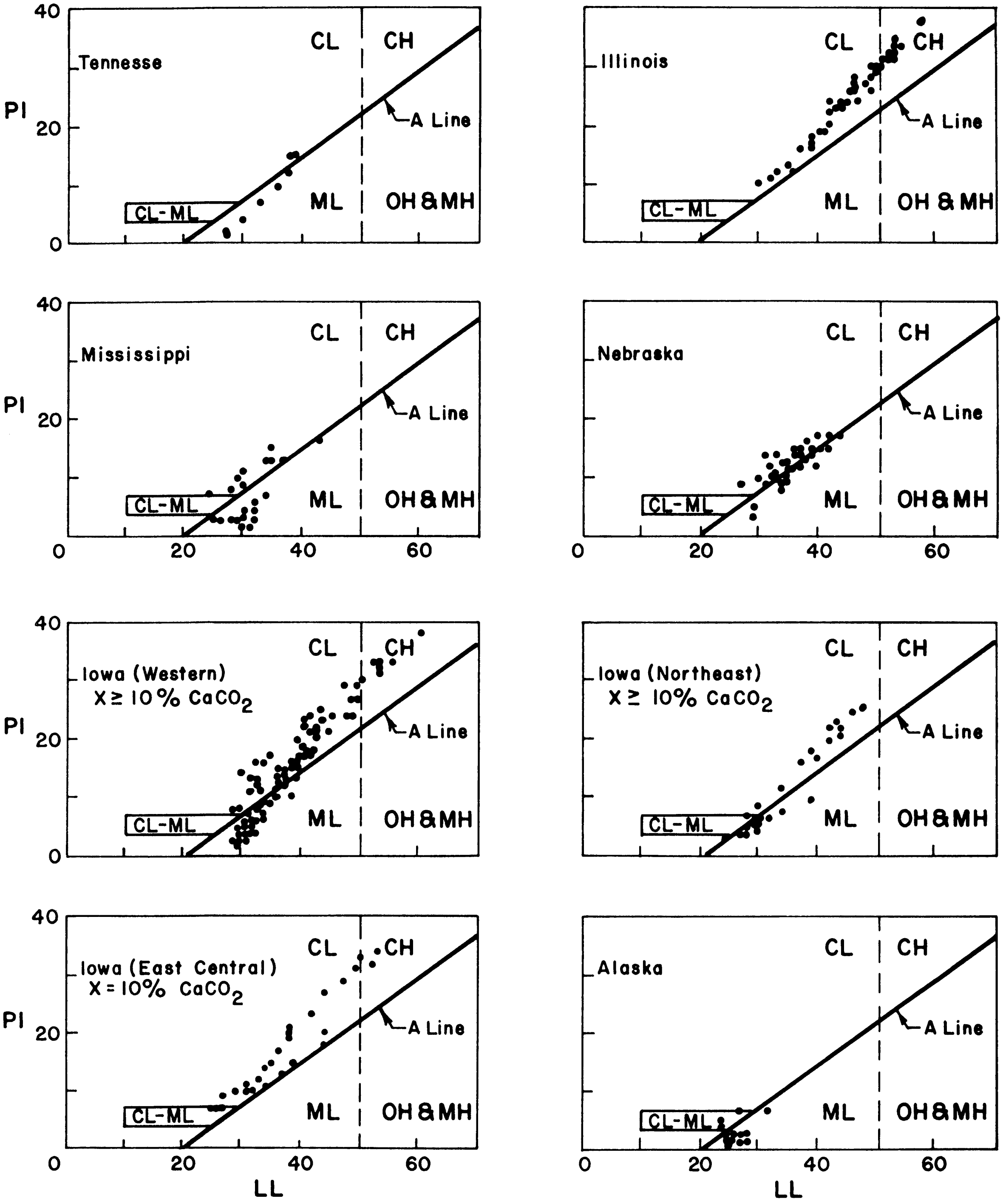

Figure 8. Plasticity data for loessial deposits throughout the United States. After Sheller (2).

The highest values of cohesion were reported for loess samples of high density, high clay content, and low moisture content. Cohesion values as high as 65 psi have been observed (15). Conversely, low density, silty loess samples tested at high water contents, produced Mohr envelopes with cohesion intercepts equal to zero.

Although the variability of the angle of internal friction (ϕ) appears to be confined to a narrow range, some controversy exists regarding the strength of low density silty loess at high water contents. Some authors have observed a complete loss of strength below a minimum consolidation pressure of approximately 10 psi (3,9,15,31), while other authors have not observed this phenomenon (1,17,28). Some investigators have explained the lack of shear strength at low consolidation pressure by stating that a minimum degree of consolidation is required to produce grain to grain contact and thus shearing resistance (3,9,15).

Without more detailed information on how the triaxial testing was conducted, it is difficult to ascertain the actual cause for this lack of strength at low confining pressures. One explanation may be presented utilizing Kane's critical water content concept (17). First, it should be noted that the samples exhibiting a lack of shear strength at low confining pressures were wetted. However, no reference was made to B value checks to determine the degree of saturation. It may be reasonable to assume that while the samples had been wetted, they were not completely saturated.

If the sample was wetted, the clay binder would become saturated prior to saturation of the sample as a whole. It is doubtful that substantial pore water pressures would develop in the clay binder at this point. However, the clay binder would be in a state of near saturation under unconfined conditions and as such, strength would tend to be very low.

Variability of Index Properties of Loess with Distance from the Source

Although index properties within a given deposit of loess tend to vary within narrow bounds, some trends have been noted with respect to the distance from the source. Investigations in the midwest and south (5,11,20) indicate an increase in clay content and decrease in total thickness with distance from the source. Studies in Iowa (5) and Mississippi (20) note that as clay content increases, silt content decreases with sand content a uniform, minor constituent.

Variation in clay content tends to affect the engineering and other properties. As clay content increases, natural water content and density also increase (6). Thus, natural water content and density can be expected to increase with distance from the source.

A linear relationship between thickness and the logarithm of distance from the source has been established (11) for midwestern loess deposits. While this relationship is undoubtedly true for some deposits, in many cases thickness is highly variable on a local scale with no clear trends discernible. When a high degree of variability is encountered it is usually due to hummocky terrain with maximum thicknesses near the crest of hills and minimal deposits in intervening depressions (19).

Depth Effects

It is not possible to generalize when discussing the variation in textural composition with depth other than to say that changes in the relative percentage of the sand, silt, and clay constituents with depth are usually minor. In some areas sand content has been found to increase slightly with depth while clay content remained constant, or showed a minor decrease (22). Conversely, some vertical sections exhibit a uniform percentage of sand with depth while clay content remains constant until increasing slightly at the base of the unit (13). Except for isolated cases, variations in constituent percentages did not vary more than 7-8%.

In-place density and natural water content demonstrate a more consistent trend with depth than does textural composition. Ignoring fluctuations in the upper 6-7 ft., both density and water content tend to increase with depth.

CURRENT PRACTICE IN CUT SLOPE DESIGN

Comprehensive design criteria that specifically address the unique engineering properties of loessial soils are applied by a limited number of state transportation departments. Letters were sent to various state transportation departments by WSDOT requesting information pertinent to Phase I of the research program. The emphasis of the request was on design guidelines for cuts in loess as well as any information on physical properties and slope performance of loessial soils compiled within the respective states.

The design criteria developed by the Missouri State Highway Department (25) is based on the most comprehensive study to date, and is the most recent. Evaluation of cut slope performance in Tennessee loessial deposits was conducted by the Tennessee Department of Highways (30,31). Other states contacted indicated that either no special design considerations were given to cuts in loessial deposits, or slopes were flattened to between 2:1 and 4:1. A summary of design methods employed by various states is presented in Table 1.

Missouri State Highway Department

The Missouri design specifications utilize three main criteria: 1) gradation boundaries similar to those established by Holtz and Gibbs (15) for silty and clayey loess; 2) the critical water content concept developed by Kane (17); and 3) experience from studying the relationship between slope performance and physical properties for 106 highway cuts in

Table 1. Summary Table

State	Design Procedures
Arkansas	No set design procedure was indicated. Vertical cuts are often utilized with benches employed for cuts exceeding ∼25 ft. in height. Bench widths are approximately 10 to 15 ft. wide and placed on a 1-ft. grade toward the backslope. Drainage ditches are usually constructed near the top of the cut and at the toe with ditch paving utilized on the benches to channel drainage. Collection pipes are used to convey the runoff from the top of the cut and benches to road level.
Indiana	Experience with cut slopes in loess is limited. Vertical cuts are employed with 10 ft. wide benches constructed for cuts over 15 ft. high. Paved interceptor ditches are installed above the cut to prevent runoff flowing over the face.
Iowa	IDOT does not employ any special design techniques for loess. Their normal backslope design is utilized with 15 ft. wide benches placed every 25 ft. of vertical height and are sloped to the back of the cut. Drains are employed when the loess overlies a relatively impermeable layer to drain the contact.
Kansas	Slopes of 3:1 or flatter are usually employed although some 2:1 benched slopes have been constructed. Slope performance is generally good; however, some erosional problems have been experienced when runoff has flowed over the slope face.
Missouri	Employ both vertical cuts and flattened slopes (<2.5:1) based on grainsize distribution and water content. Slope stability analysis used for saturated deposits
Nebraska	Although vertical cuts have been constructed for some minor roadways, slopes flattened to 3:1 are typically employed. Flattened slopes perform well once a vegetative cover has been established. Nebraska prefers the use of dikes to ditches when runoff must be restricted on the cut face.
Ohio	No special considerations, 2:1 slopes are employed.
Tennessee	Slopes are cut to 2:1 or flatter with 15-25 ft. benches at 20-25 ft. intervals.

loess. For correlative purposes MSHD redefined Holtz and Gibbs silty-clayey loess boundary with clayey loess defined as having either 22% or more finer than 7 micron size or 16% or more finer than 2 micron size.

The field investigation consisted of observations regarding the type and degree of failure, exposure, slope, and stratigraphy. In addition to field observations, sampling was conducted in order to determine physical properties such as moisture content, Atterberg limits, and gradation. The degree of disturbance caused by various drilling and sampling techniques on "undisturbed" samples were compared to samples cut by hand. The effects of these techniques on density and water content were examined.

Upon correlation of field observations with physical properties it was concluded that all degradation or failure could be directly related to gradation and/or water content. Slopes cut in soils exhibiting erosion problems, including piping, fell within the silty loess boundary. Slopes exhibiting volume change problems (sloughing and slabbing) and sliding failures were cut in clayey loess. Slopes that failed due to undercutting, primarily caused by truncated water tables, were found in both silty and clayey loess with failure the result of high water content. Frost damage was restricted primarily to vertical cuts in silty loess with the failure mechanism analogous to subgrade frost heave.

The orientation of the cut face was determined to be a contributory factor influencing slope performance, particularly for vertical slopes. A significantly greater percentage of north facing vertical slopes experienced frost damage than any other orientation. Water contents were found to be higher, averaging 20.0% in contrast to 18.4% for all other exposures.

It was concluded that vertical slopes perform well in silty loess when water contents are maintained below 17%. Slightly higher water contents (less than 20%) could be tolerated with a favorable exposure (between southeast and southwest). Flattened slopes should be used for silty loess with high water contents and for all cuts in clayey loess. Although 2:1 slopes are generally flat enough from a stability point of view, slopes flattened to 2.5:1 show much less degradation due to erosion. Where water tables are truncated much flatter slopes could be required due to seepage forces.

When vertical cuts are employed, the cut is typically benched when the total height exceeds 25-35 ft. Benches are placed approximately every 20 ft. vertically with a width of 15-20 ft. The benches have the dual purpose of limiting erosion and providing increased stability for the overall slope.

In some cases, composite cuts can be constructed utilizing both flattened and vertical slopes. In deep cuts it is common to find that a flattened slope is necessary for the lower portion of the slope due to high water content while a vertical cut may be employed in the upper section. There is nothing to prevent this geometry from being considered, provided it meets the stability requirements of the component parts as well as the overall cut.

The Missouri investigation suggests some problems with the drilling and sampling methods most commonly used to obtain "undisturbed" samples, particularly at high water contents. Undisturbed samples were obtained by both Shelby tubes and "Denison" double tube samplers. Whenever possible, densities for down-hole samples were compared to hand-cut samples. In all cases down-hole samples were found to be denser, indicating compression during sampling. The largest discrepancies between hand cut and down-hole samples were found when water contents were in excess of 18%.

A similar investigation into sampling effects was conducted on Bulgarian loess (24). It was found that samples obtained utilizing Shelby tubes had unconfined compressive strengths approximately twice that of hand cut samples for a water content of 22 ± 0.8%. Thus, sampling disturbances result in an unconservative adjustment to the shear strength of loessial soils, particularly at water contents in excess of 18%.

The general conclusion of the Missouri report regarding vertical versus flattened slopes is that vertical cuts should be restricted, but not eliminated. Provided the deposit meets the gradation and moisture criteria outlined, a vertical cut is the preferable choice, particularly since silty loess not only performs the best in vertical cuts but tends to exhibit extensive erosion on flattened slopes.

Tennessee Department of Transportation

The Tennessee Department of Transportation (TDOT) has developed some useful design criteria, particularly with respect to erosion control. Their research (30,31) indicated that, in general, vertical cuts were performing better than flattened slopes. Even so, recent correspondence with TDOT indicates that flattened slopes are being employed. Presently, TDOT designs cut slopes 2:1 or flatter with 15 to 25 ft. benches at 20 to 25 ft. vertical intervals with 3-5 ft. granular layers across poorly drained areas (29). Although no explanation was given for this discrepancy between research findings and design practice, a passage from a 1965 research report (31) indicates the decision may be administrative and based on considerations other than slope performance.

> It is generally believed by some in the department that since loess does possess the rather unusual characteristic of standing on very steep slopes, this inherent characteristic should be taken advantage of in many cases by constructing slopes with near-vertical faces. This belief is shared only by those persons in the department that are trained or experienced in soil engineering. Design and construction personnel have maintained that conventional slopes (1.5:1 to 2.5:1) are much more desirable, not only from an aesthetic viewpoint but for maximum stability as well.

Regardless of the slope design employed, surface drainage should always be controlled, and TDOT has developed some useful guidelines for this purpose. Surface drainage must be diverted prior to opening the cut. This is usually accomplished by cutting a shallow, flat-bottomed, or dish-shaped ditch 10 to 15 ft. behind the top of the proposed cut slope. This ditch keeps surface water from flowing over the face of the open cut, and should be either paved, sodded, or seeded depending on the gradient.

The natural vegetation, particularly between the top of the cut and the ditch, should be disturbed as little as possible. Once the cut is started, construction equipment must be prevented from operating along the edge of the cut. Machine vibrations tend to weaken and fracture the cut face and may lead to failure. Cuts over 25 ft. high should be benched at 20 to 25 ft. vertical intervals with 15 to 20 ft. bench widths. Benches should be sloped toward the back of the cut to prevent water from flowing over the face. Side ditches are generally required and should meet the same guidelines as the upper ditch as far as geometry and erosion control are concerned. While the cut face should not be seeded for vertical cuts, conventional slopes (2.5:1 or less) should be sodded, or heavily seeded immediately after the cut is completed.

Upon completion of a cut, proper maintenance is required. For conventional slopes, heavy vegetation is required due to the high susceptibility of loess to erosion. If erosion gulleys do develop, they should be repaired immediately, as they tend to enlarge rapidly once initiated. After vegetative cover has been established it must be fertilized regularly. Newly seeded slopes should be heavily mulched with some type of protective cover, such as straw. Vertical cuts should maintain a heavy vegetative cover between the top of the cut and the drainage ditch. In addition, any material spalling from the face should be left at the toe to help stabilize the face and protect the toe from undercutting by runoff.

Other States

States other than Missouri and Tennessee responding to WSDOT's request for information report fairly good success with their respective methods. However, most respondents indicate only limited experience in cut slope design in loessial soils. No states other than Missouri and Tennessee conducted detailed investigations into cut slope performance. In most cases proper drainage, particularly above the cut, is emphasized regardless of whether vertical or flattened slopes are employed.

The WSDOT has used various designs for cut slopes in loess. In the central and western sections of the deposit, many cuts have been constructed between 0.5:1 and 0.25:1. In the wetter eastern section of the deposit, most of the slopes have been cut at approximately 2:1. In general, drainage and benching have not been included. Also, to keep as much land in production as possible, farming has been allowed up to the edge of the cut. The most recent WSDOT design for a cut in silty loess near Walla Walla calls for 0.5:1 benched cuts with berms above the crest of the cut for drainage; however, this design has not been implemented yet.

INDEX PROPERTIES OF SOUTHEAST WASHINGTON LOESS

Origin

Loessial deposits blanket the majority of southeastern Washington and extend into northern Idaho and northeastern Oregon. Traditionally the deposit has been subdivided into four formations: Palouse Loess, Nez Perce Loess, Ritzville loess, and Walla Walla loess. The earliest engineering reference to these subdivisions was by Ekse (8). The formation boundaries are based on pedological classification, making their value with respect to engineering properties questionable. Figure 9 shows the deposit with the formation boundaries.

The source material for the southeastern Washington loess deposit is still a matter of debate. Various investigators have proposed sources ranging from northwest to southwest of the deposit with the Ringold Formation, centered in the Pasco Basin, the most widely accepted origin (56).

Field Study

The field study had two primary goals: (1) evaluation of performance of existing highway cut slopes and associated failure mechanisms; (2) collection of a sufficient number of soil samples to delineate the variation in index properties with location.

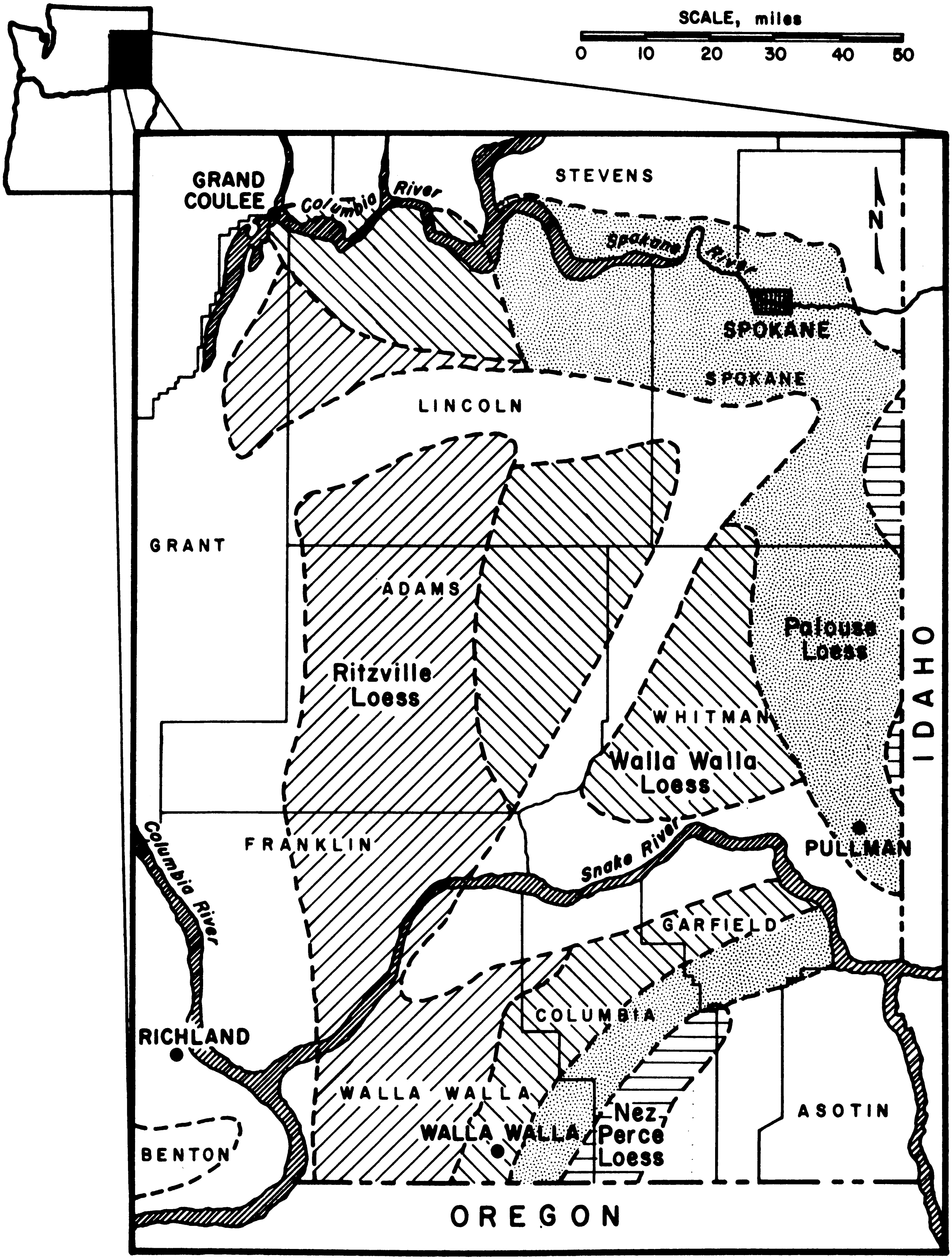

Figure 9. Study area for southeastern Washington loess with associated formation boundaries.

None of the proposed lab tests required undisturbed samples. As a result, 67 bag samples were collected by hand augering. All bag samples were acquired from road cuts. In general, samples were collected by augering horizontally into the road cut 3 to 4 ft., and sampling within the last foot. Samples were placed in plastic bags and immediately sealed to prevent moisture loss.

To minimize variation in the percentage of clay and organic matter due to A and B soil horizon development, samples were collected at a depth of 10 ft. from the ground surface, within the C horizon. The only exceptions to this procedure occurred when the road cut was not of sufficient height to make sampling to 10 ft. practical, or when vertical sections were desired, in which case samples were obtained at set increments.

Although the observation and evaluation of slope failures were considered an integral part of the field study, sample locations were not chosen based on slope performance. Instead, an effort was made to pick sites evenly spaced throughout the study area. In this way trends in index properties and the validity of the formation boundaries previously outlined could be evaluated. Figure 10 denotes the sample locations.

Lab Tests

As was indicated in the literature review, grain size distribution and natural water content appear to be the best indicators of potential slope stability problems. Other parameters considered useful, either as an indicator of possible stability problems or as a basis for comparison with other deposits, include Atterberg limits, specific gravity, density and shear strength. Shear strength was not evaluated in this study.

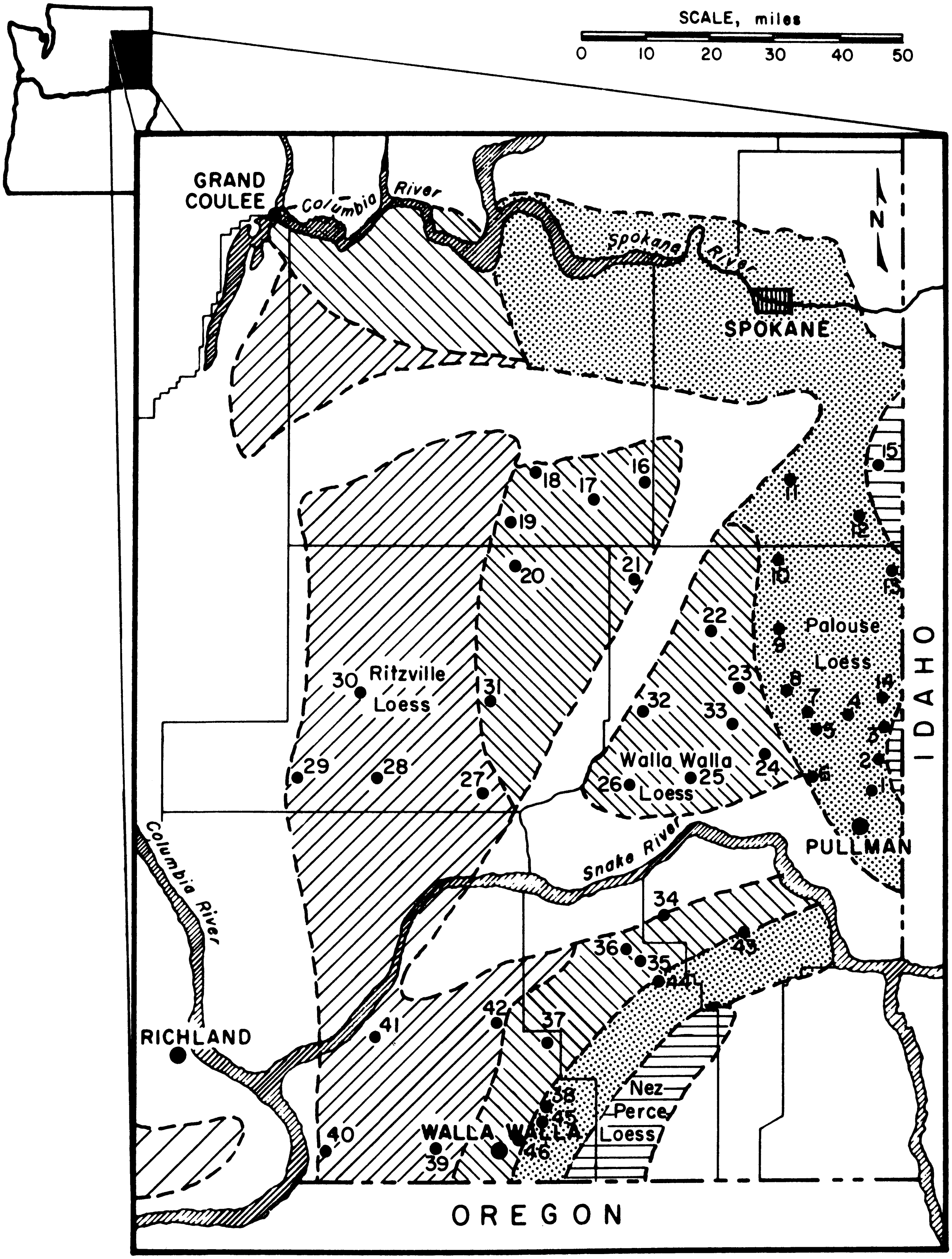

Figure 10. Sample locations for southeastern Washington loess field study.

Atterberg limits (liquid and plastic), grain size analysis, and water content were conducted on 40 representative samples, while specific gravity was determined for 18 samples. All tests were performed in accordance with ASTM standards in the soil mechanics laboratory at Washington State University.

Specific Gravity

Specific gravity of southeastern Washington loess varied within narrow limits. Values ranged from 2.67 to 2.74 with a mean of 2.71 for the 18 samples tested. The consistency of the test results led to the decision not to conduct specific gravity tests on all samples. It was felt that the lab time could be better spent increasing the data base for grain size distribution and Atterberg limits tests.

Density

Although in-situ densities were not measured, a limited amount of data are available from a previous investigation, as well as WSDOT laboratory tests. Lobdell (21) reported dry densities ranging between 95 to 98 pcf in Palouse loess. Laboratory data provided by WSDOT for the Pullman to Wawawai Road specify densities ranging from 83.8 to 108.5 pcf with a mean of 94.9 pcf for 29 samples. Water contents for the WSDOT samples ranged between 20.0 and 35.7%.

Lobdell (21) obtained block samples in the form of 6-inch cubes from an excavation site at Washington State University. Thus, the values he reported should be an accurate indication of in situ dry density for the eastern extreme of the deposit. WSDOT may have utilized Shelby tubes in obtaining the samples collected for the Pullman-Wawawai road. As previously noted, down-hole sampling in loess at water contents in excess of 18% tends to produce compression in samples, resulting in sample densities higher than actual in-situ densities. Since the lab data indicate water contents ranging from 20.0 to 35.7%, it is probable that compression occurred during sampling. Therefore, the dry densities cannot be reported with total confidence.

It should also be noted that all the data obtained are from the eastern extremity of the study area. As discussed in the literature review, density tends to increase with distance from the source. With the source to the west of the deposit, it is likely that in-situ density increases from west to east. Thus, the density data reported by Lobdell (21) would tend to provide an upper bound for the deposit.

Gradation

Grain size analyses were performed on 40 samples of southeastern Washington loess. The range in grain size distribution is presented in Figure 11 and corresponds closely with the boundaries established by Holtz and Gibbs. Of the 40 samples tested 10.0% were classified as sandy loess, 67.7% silty loess, and 25.0% clayey loess. Individual gradation curves are presented in the Appendix.

Grain size analysis is the primary laboratory test utilized when attempting to define the variation in index properties with location for loessial soils. As was established in the literature review, clay content, water content and density all tend to increase with distance from the source. In addition, it has been determined that specific failure modes are associated with certain ranges in grain size distribution.

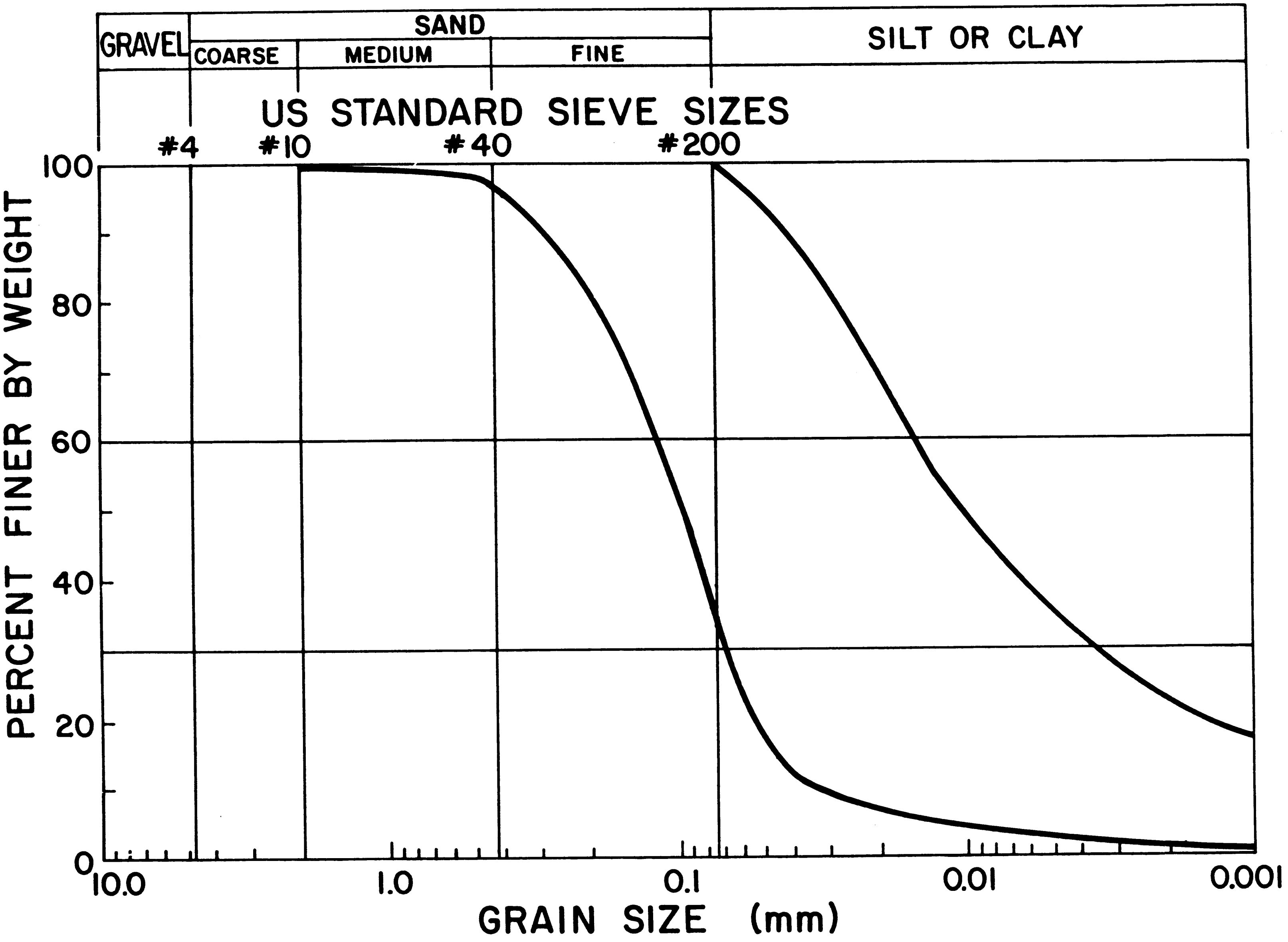

Figure 11. Range in grain size distribution for 40 samples of southeastern Washington loess.

Although 40 samples do not constitute a large enough data base to provide a definitive answer with regard to source or distribution, it does supply sufficient data to establish general trends within the deposit. Figure 12 indicates the locations of three cross sections constructed through the deposit based on the grain size analyses; one trending east-west and the other two north-south. Figure 13, the east-west cross section A-A', demonstrates a general increase in clay content to the east and a decrease in sand. Figure 14, the western most north-south cross section B-B', reveals fairly constant clay-silt-sand ratios with only local fluctuations. The eastern most north-south cross section C-C', Figure 15, is similar to Figure 14 in that the relative percentages of sand, silt and clay remain fairly constant. However, cross section C-C' has a higher clay content and lower sand content than B-B' as would be expected because of its greater distance from the source.

Clay content (<2 μm) was contoured for the study area and is presented in Figure 16. Although two minor anomalies are present, a definite trend of increasing clay content to the east is apparent. As established above, sand decreases from west to east. These facts in conjunction with the cross sections, suggests that the source material was to the west of the deposit with no major north or south directional component.

None of the data collected supports the use of formation boundaries proposed by Ekse (8) (Figure 9) as engineering units. While the subdivisions may be of use from an agricultural or pedological point of view, the data clearly demonstrate that with regard to index properties, variations can be expected to trend east-west independent of formation boundary. Figure 17 indicates gradation boundaries for southeastern Washington loess based on testing to date.

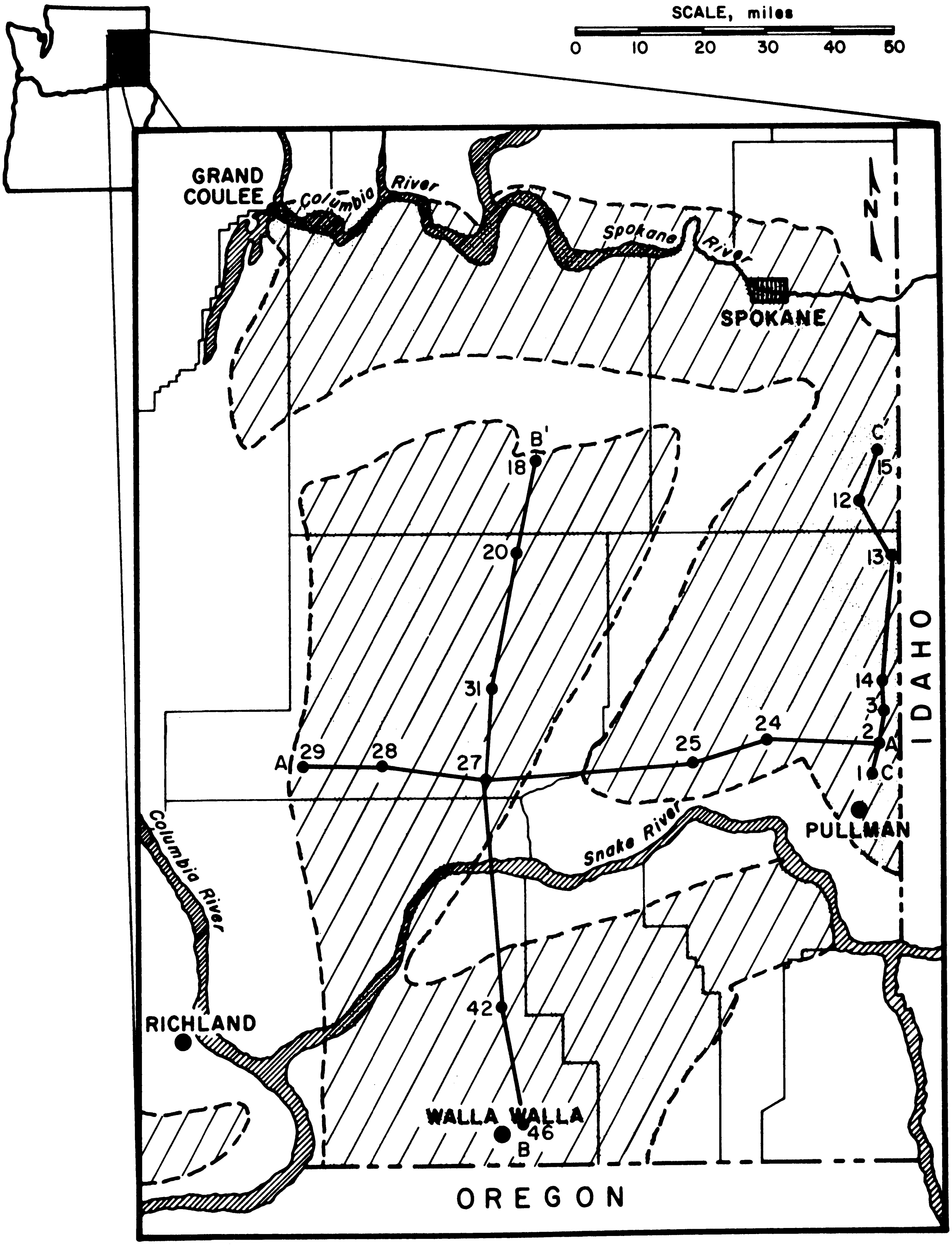

Figure 12. Location map for cross sections A-A', B-B', and C-C'.

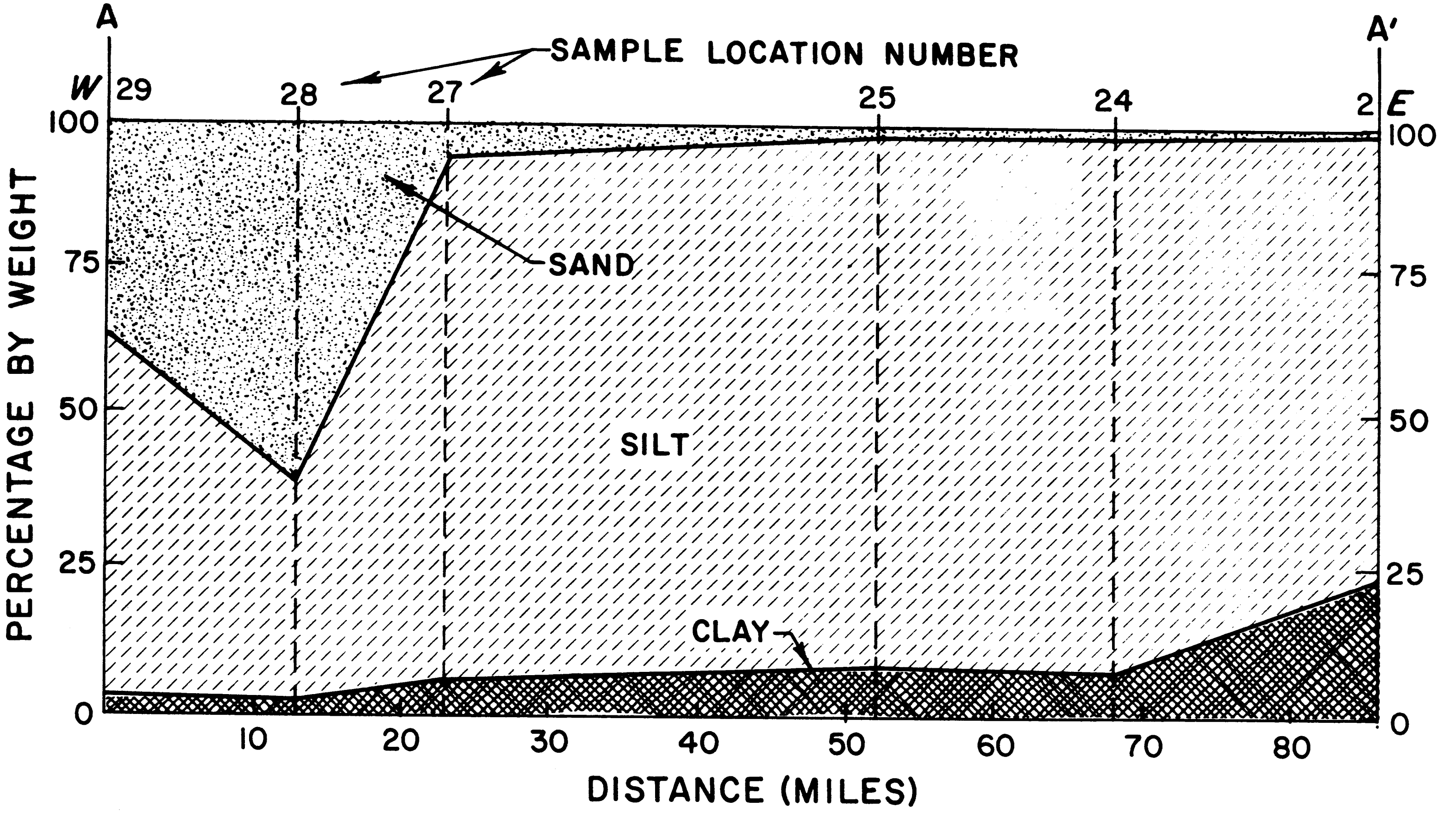

Figure 13. Cross section A-A'.

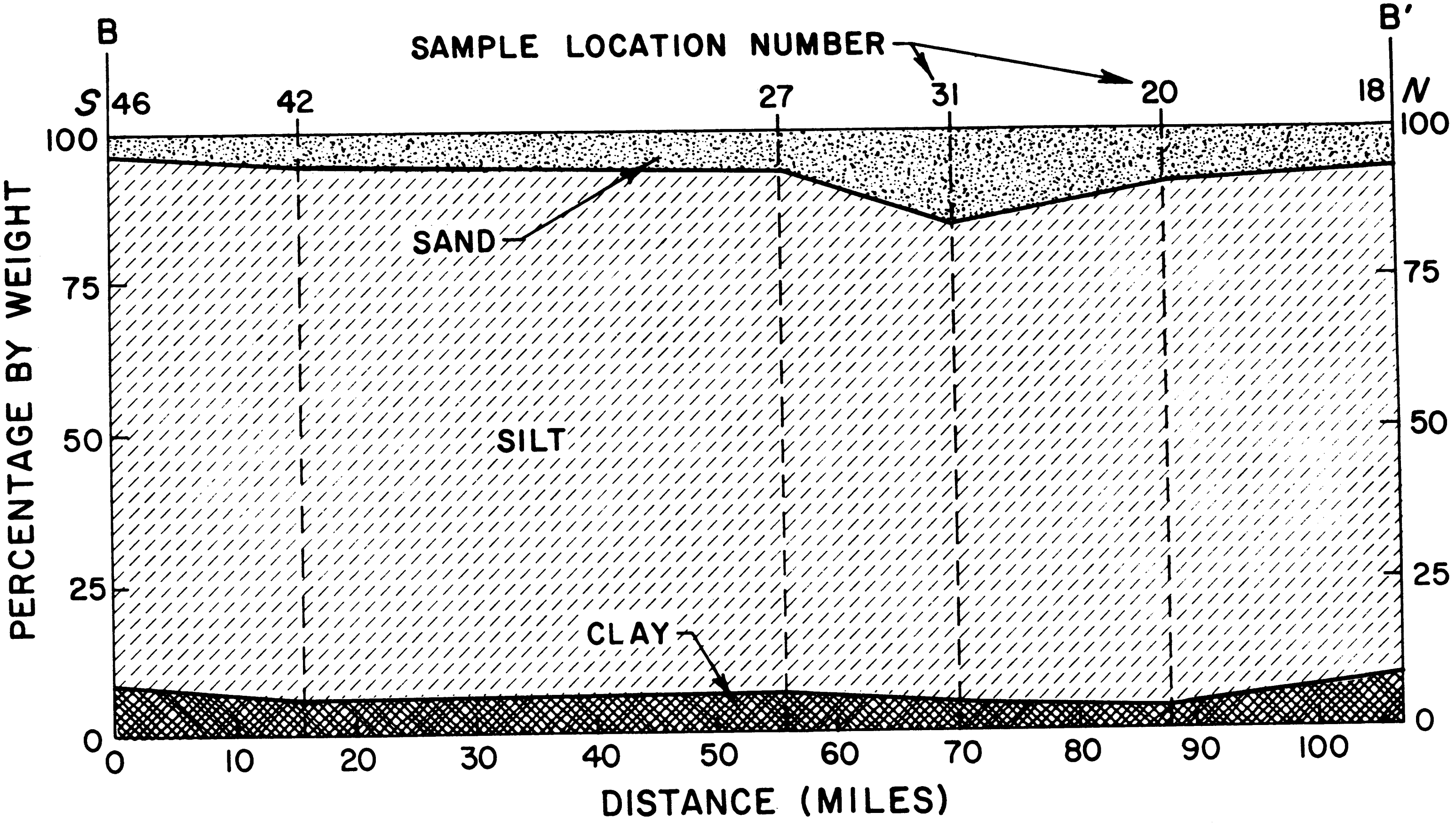

Figure 14. Cross section B-B'.

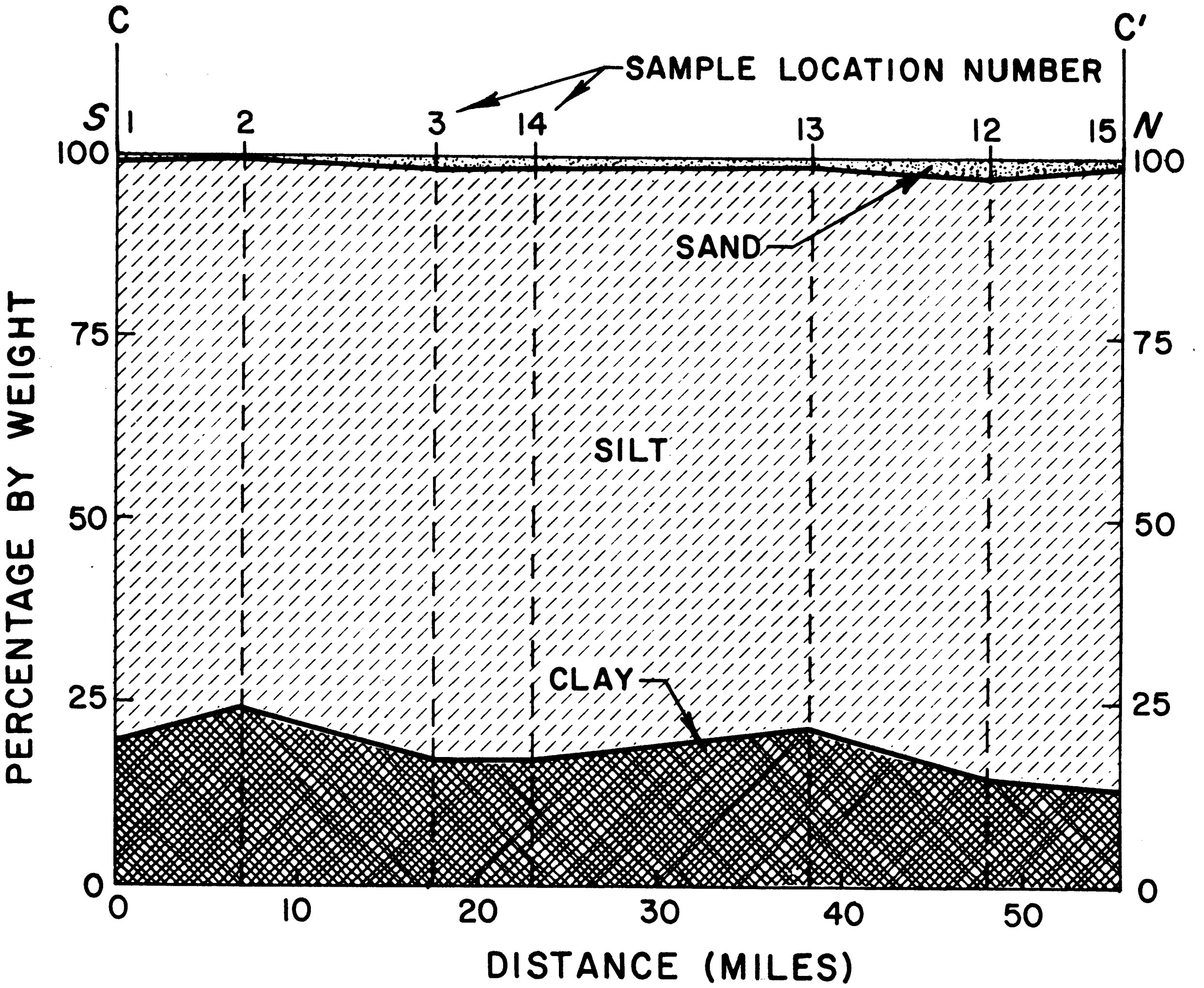

Figure 15. Cross section C-C'.

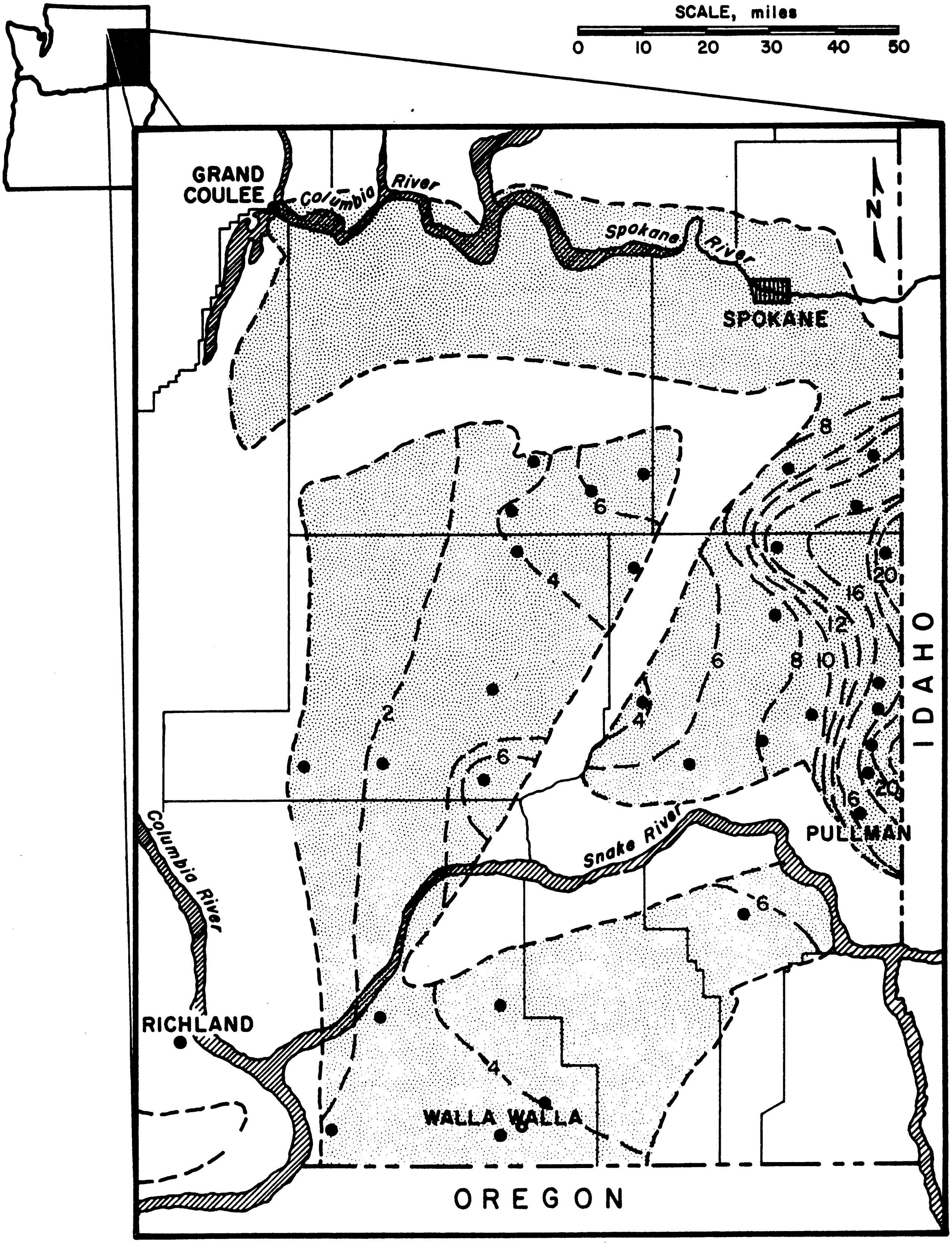

Figure 16. Contour map of clay content (in percent) for southeastern Washington loess.

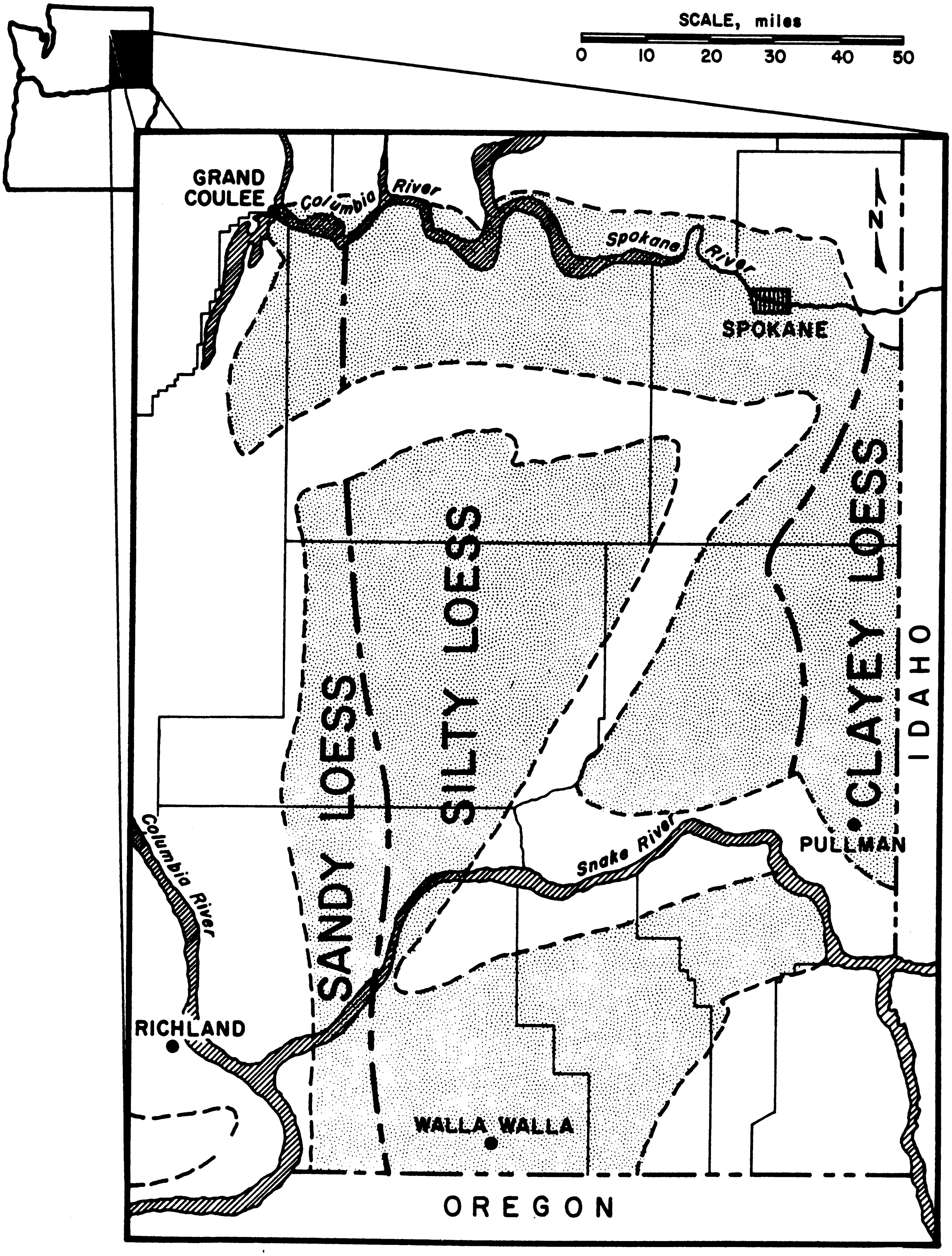

Figure 17. Approximate gradational boundaries for southeastern Washington loess.

Figure 18 is a vertical profile collected at sampling site B-25 and consists of five discrete sampling points. As illustrated in the figure, little variation in the relative percentages of the sand, silt, and clay fractions is expressed. While the percentage of sand size particles varies by less than 1%, clay content (<2 μm) varies up to 5%, still relatively minor for a natural soil.

Water Content

Of the 40 samples tested, natural water contents were obtained for 22 samples. Although the minimum horizontal distance into a cut slope required to produce an accurate determination of natural water content has not been established, it was felt that 3 to 4 ft. would provide a reasonable approximation. As a result, water content was determined if the 3-ft. minimum depth requirement could be met. In cases where it was not possible to auger to 3 ft., primarily due to calcium carbonate induration (hardening), water content was not measured.

For the samples tested, water content ranged from 4.5% to 27.7%. As might be expected, water content shows a high degree of variability from location to location. Even so, a general trend exists with water content increasing from west to east. The directional variation in water content may be attributed to two factors. First, the clay content increases from west to east as determined by the grain size analysis. As previously indicated, water content tends to increase with increasing clay content. Secondly, mean annual precipitation tends to increase from west to east as illustrated in Figure 19.

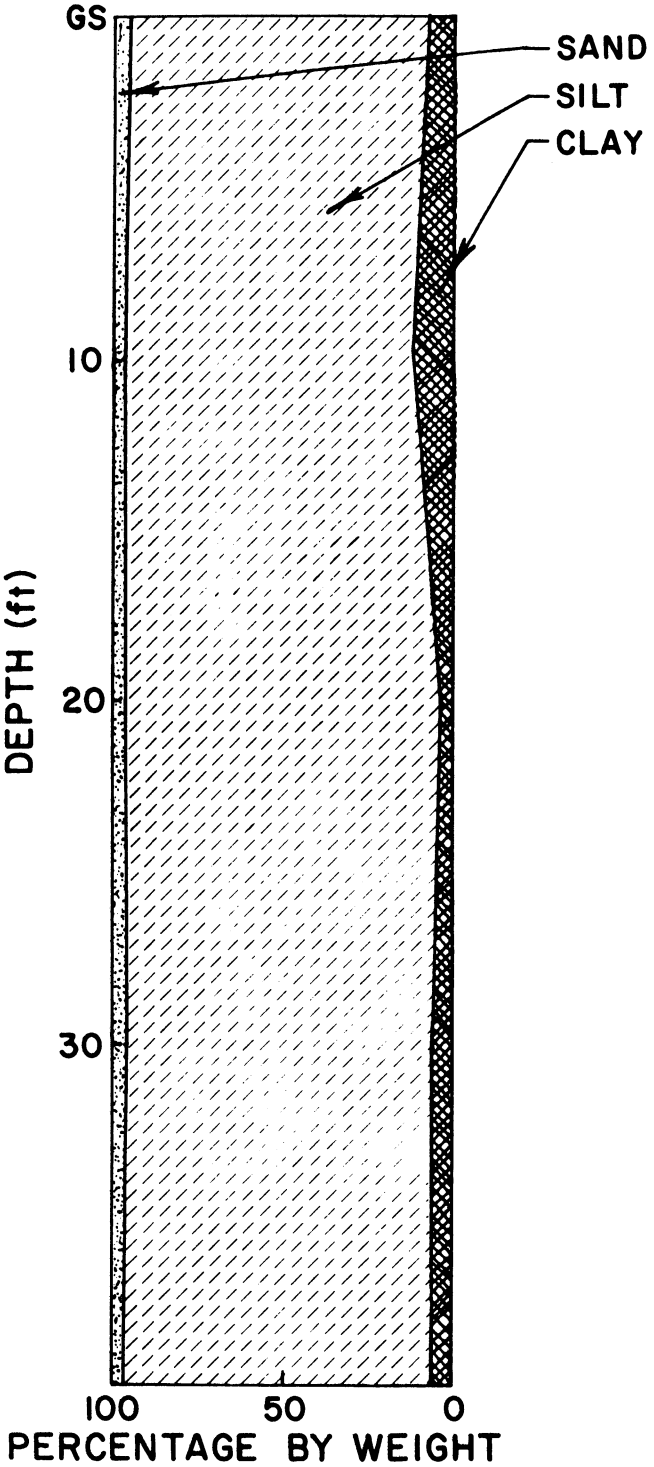

Figure 18. Variation in textural composition with depth for sample location B-25.

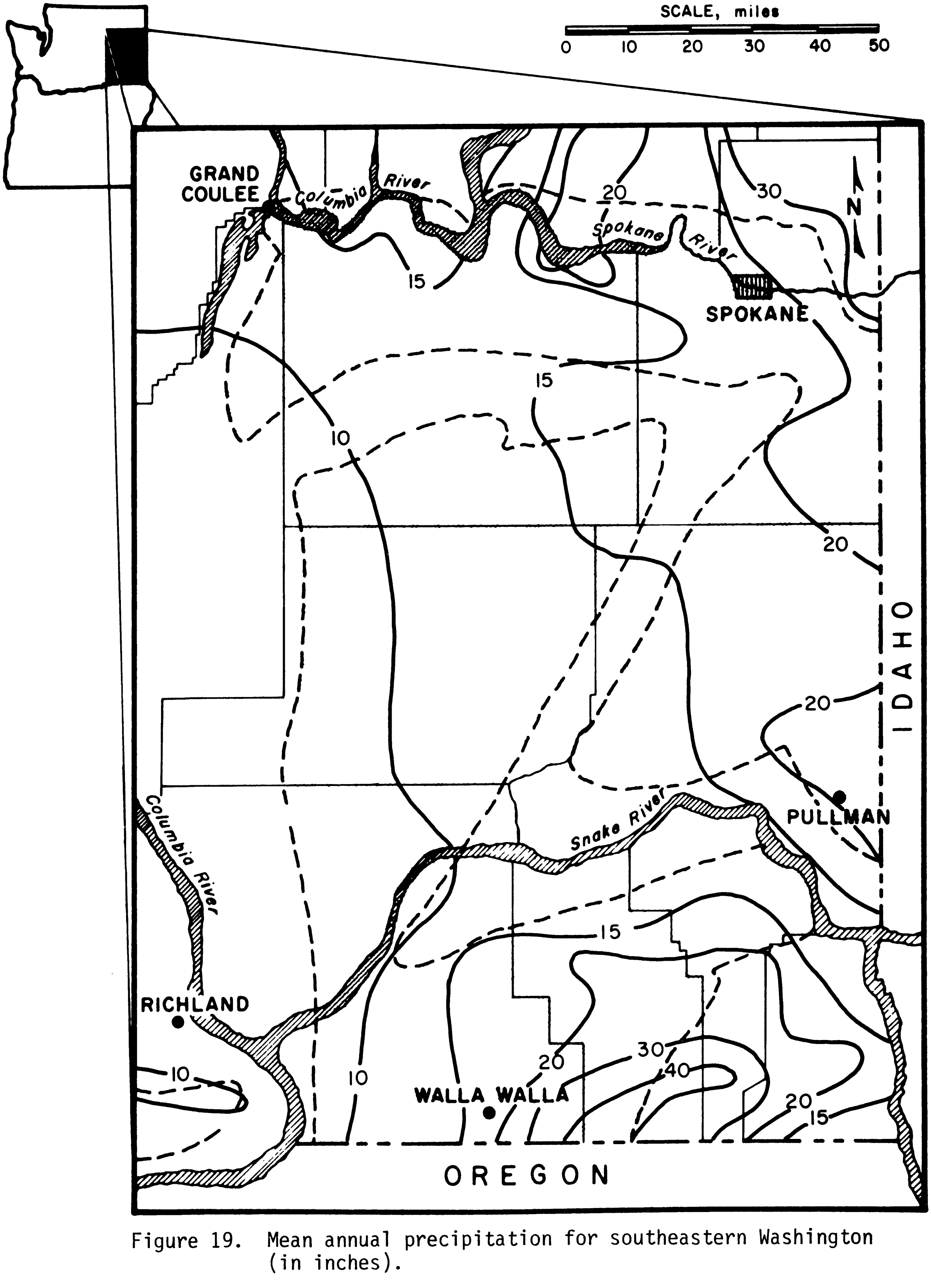

Figure 19. Mean annual precipitation for southeastern Washington (in inches).

Plasticity

Plasticity characteristics were evaluated by the Atterberg limits tests. Plastic and liquid limits tests were conducted on 40 samples and plotted on a plasticity chart (Figure 20). Upon examination of the plot and the grain size distributions, two groupings of the data can be made. Silty loess tends to plot with liquid limits ranging from 13.6 to 31.7 and plasticity indexes of 0 (nonplastic) to 10.5. Clayey loess has liquid limits that vary between 33.2 and 48.8 with plasticity indexes ranging from 11.4 to 27.1. A number of silty loesses, as well as the two sandy loesses tested were not of high enough plasticity to complete either liquid or plastic limits tests.

Calcium Carbonate

During field sampling various forms of calcium carbonate were encountered. In most cases calcite was present as either root fillings or nodules. To a lesser extent calcite was found to exist as indurated sheets lying 6 in. to 1 ft. below the surface of a cut face. This appears to be an evaporation phenomenon similar to that noted in Mississippi (20). Due to the discrete nature of most calcite deposits, the fact that calcium carbonate was not sampled in an area where it might be expected, does not necessarily imply that it is absent from the area as a whole.

It would appear that the presence or absence of calcium carbonate is related to mean annual precipitation. In areas averaging greater than 20 in. of precipitation per year, no samples containing calcium carbonate were encountered. Conversely, a large majority of samples collected in areas where mean precipitation was less than 15 in. contained a significant quantity of calcite.

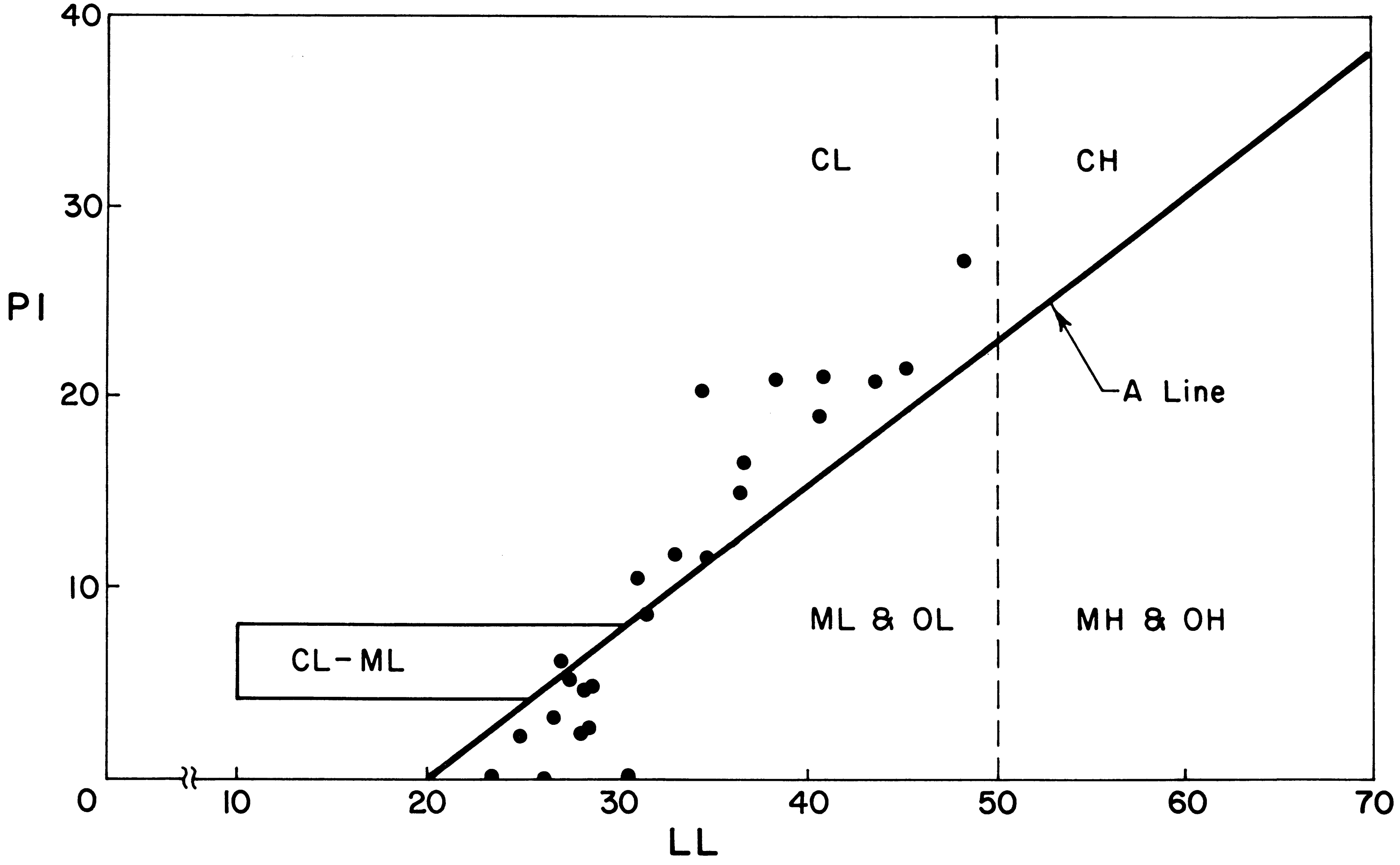

Figure 20. Plasticity data for southeastern Washington loess.

Relationship between Southeastern Washington Loess and Other Deposits

Based on present laboratory results southeastern Washington loess appears similar to loessial deposits within the central United States. Gradation boundaries are very close to those found by Holtz and Gibbs (15) for Missouri River Valley loess. Plasticity tends to be slightly lower in Washington loess than other deposits, possibly due to greater illite and lower montmorillinite content. Other properties such as calcium carbonate occurrence, variation of textural components with depth as well as specific gravity appear consistent with results obtained for other deposits.

FAILURE MECHANISMS ASSOCIATED WITH SOUTHEASTERN WASHINGTON LOESS

The failure mechanisms and associated field conditions must be considered one of the most important aspects of the field study. Although time did not permit a systematic, statistical analysis of the various failure mechanisms, it is felt that a sufficient number of slope failures or deteriorations were observed to define the most common forms of slope instability for cuts in southeast Washington loess. While some failure mechanisms are similar to those found in the midwest, different climatic conditions in southeastern Washington have resulted in the absence of some failure modes common in the central United States.

Mean annual precipitation for the majority of the study area is between 10 and 20 in., substantially less than the 30 to 60 in. common in the midwest. As a result, failure mechanisms associated with truncated water tables and ice lens formation were not observed. In addition, no slabbing failures were noted.

The fact that these types of failures have not been observed locally is not meant to imply that they may be completely discounted. Although a truncated water table is uncommon in road cuts developed thus far in southeast Washington loess, highway construction or realignment could uncover such a condition, particularly near the Idaho border where rainfall tends to be higher and increased clay content results in lower permeability.

Frost damage due to ice lens formation is generally restricted to near vertical cuts in silty loess. Precipitation for the portions of the study area covered by silty loess is generally 15 in. per year or less. Consequently, the amount of near surface ground water tends to be insufficient for ice lens formation.

Slabbing is a volume change phenomenon common for vertical cuts in clayey loess. However clayey loess is limited to the easternmost 10-15 miles of the study area. Either by design or coincidence vertical cuts appear to be absent in this area, and there is little evidence of this type of failure.

Erosion

Erosion damage (including piping) was by far the most common form of slope degradation observed in silty loess. In many cases large erosion gulleys were initiated by small piping failures originating 5-10 ft. behind the top of the cut face. As the pipe enlarged, the surface caved, forming a gulley.

In virtually all cases, major erosional features were found to be the result of improper drainage or channel protection. The vast majority of serious erosion problems were observed in long cuts transecting small drainage basins with no provisions made for conveying excess runoff away from the cut. The highly erosive nature of silty loess requires the diversion of runoff from what would normally be considered insignificant drainage areas.

Figure 21 illustrates the result of truncating a small drainage area without providing a means of conveying excess runoff from the slope or providing any erosion protection. Erosion in areas such as this can be prevented by installation of small culverts. In locations involving minor cuts, topography may be such that erosion can be prevented by installing a gravel filter blanket.

Figure 22, located on highway 12 near Walla Walla, demonstrates the progressive nature of erosion in loessial soils. Erosion was initiated where this small side drainage was truncated by the highway cut to the right (of photograph) and has progressed rapidly up gradient. Erosion will continue until the overall gradient is decreased below that causing channel scour.

Figures 23 and 24 illustrate two separate points. In Figure 23 the majority of the erosion in the left portion of the photo is due to piping. To the right of the small pipes, gulley erosion is beginning to develop. Vegetation in the base of the depression as well as the shape of the developing gully indicate the gulley originated as a pipe. When the pipe enlarged to the point where the overlying material could no longer be supported, caving occurred and the overlying vegetation was deposited in the depression. This is a very common mechanism in the formation of erosion gulleys in silty loess.

The second point that should be noted is how small a drainage basin can be and still initiate erosion. Figure 24 shows the drainage area above the erosion in Figure 23. When first examined in June 1984, prior to harvesting, there was no indication that drainage was concentrating flow toward the problem area. Upon re-examination following tillage, the photograph in Figure 24 was taken which clearly shows the minor basin draining to the existing erosion. Thus, extensive erosional problems may develop from extremely small drainage basins. In this particular case

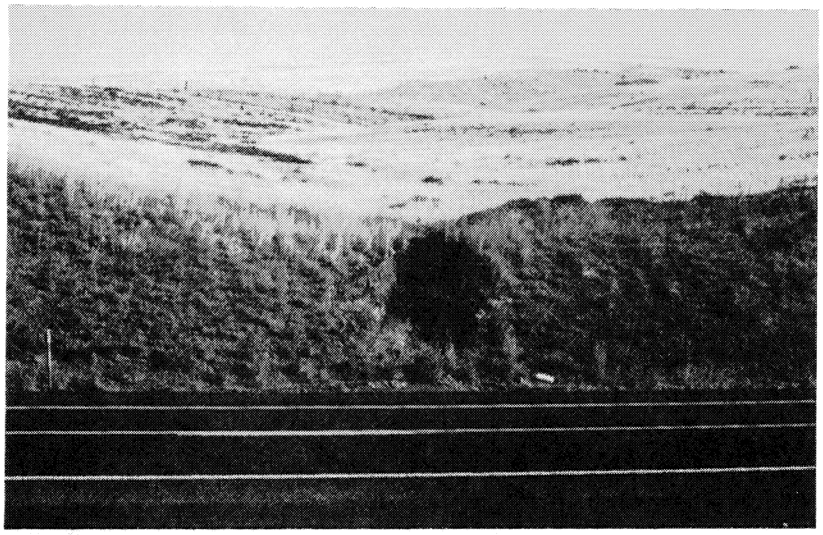

Figure 21. Gulley erosion resulting from truncation of a small drainage basin (near LaCrosse).

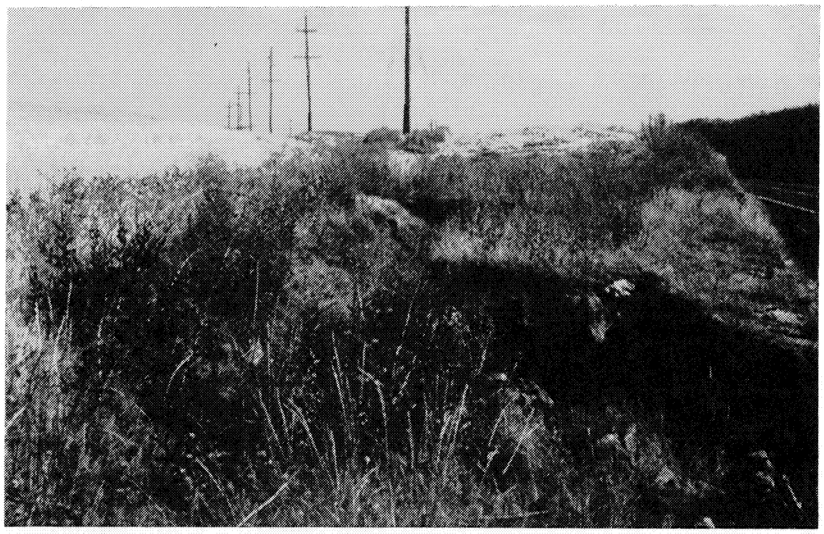

Figure 22. Gulley erosion in a side ditch due to insufficient channel protection.

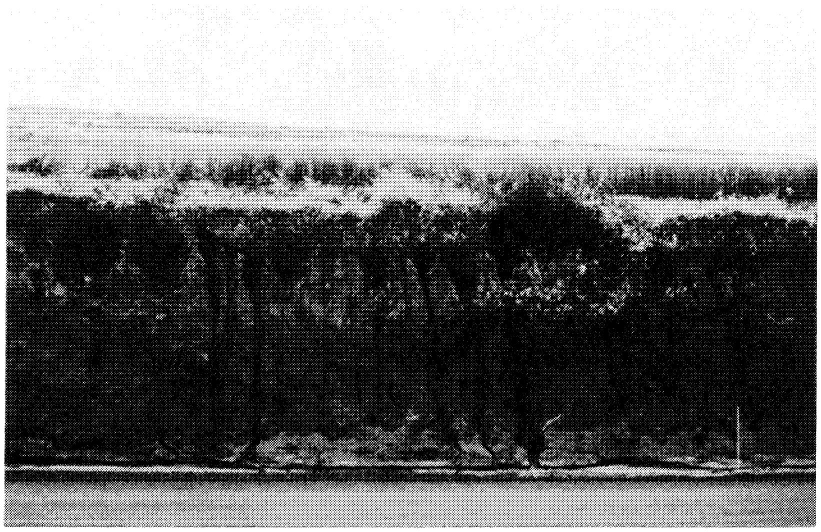

Figure 23. Piping erosion developing into gulley erosion (Highway 12 N.E. of Walla Walla).

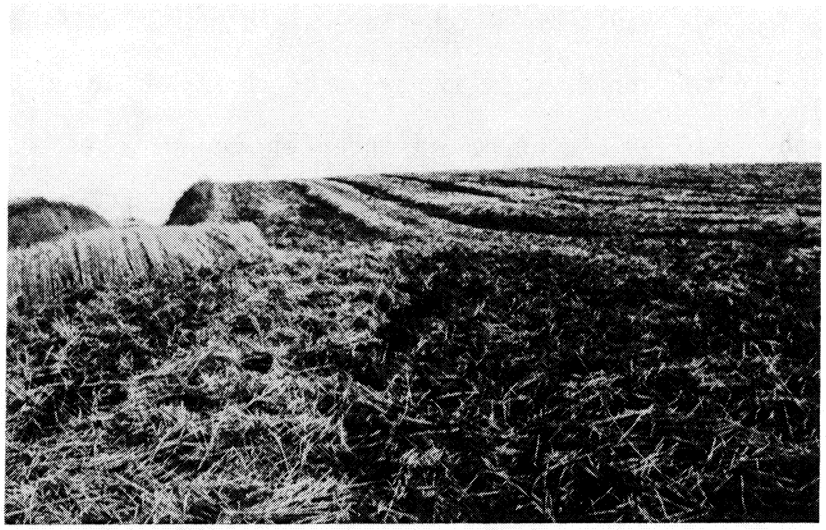

Figure 24. Small depression at center is the runoff source causing erosion in the previous photograph.

erosion probably could have been prevented by constructing a drainage ditch or dike behind the cut face to divert the surface flow.

Figures 25 through 28 demonstrate how extensive damage can be when proper drainage is not provided. The majority of damage appears to be due to a single summer storm event with a combination of piping and surface erosion taking place. The piping inlets in Figure 27 exemplify the need for construction of drainage ditches an adequate distance behind the cut slope. As can be seen in the figure, piping inlets originate a substantial distance behind the cut. Figure 28 clearly shows that the basin area is much too large to be ignored when considering drainage requirements.

Fortunately, many cuts through loess only entail truncating short lobate sections of the deposit. When this is the case, and the natural drainage is away from the cut face erosion is usually only a minor problem at most (Figure 29).

Although only a minor problem, wind erosion was observed in the western sections of the study area. Figures 30 and 31 illustrate the most common form of wind erosion in the field area. The ridges in the photographs are the result of caliche layers and not stratification.

Erosion protection devices appear to be rarely employed in Washington loessial deposits. The use of runoff interception ditches at the top of slopes, as well as side ditches, were absent for all cuts investigated. Absence of erosion control is not wholly attributable to design oversights. Copies of design drawings for a recently completed major road cut specify a berm near the crest to prevent runoff over the face and a crushed rock filter on the bench cut. However, construction of the cut did not conform to the original design considerations regarding erosion control. A continuous, near vertical cut in excess of 50 ft. high was constructed

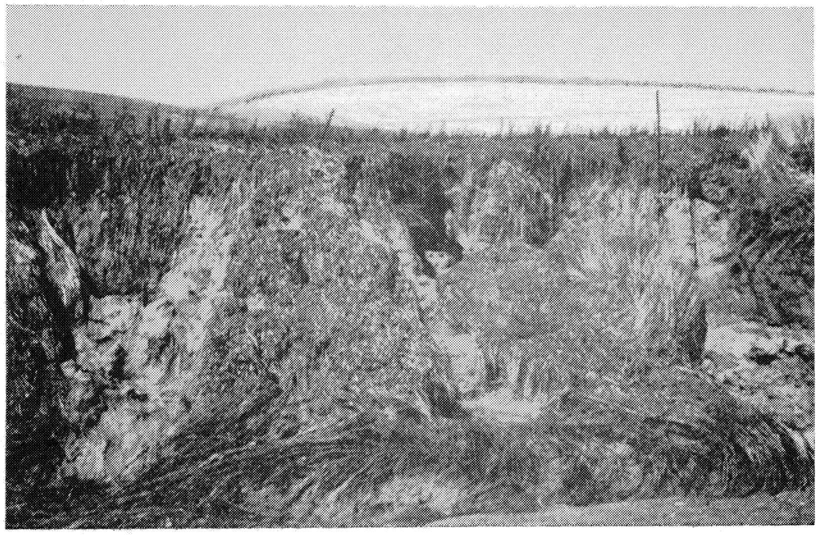

Figure 25. Area of large scale piping near Endicott. Flattened vegetation indicates flow over the slope as well as piping.

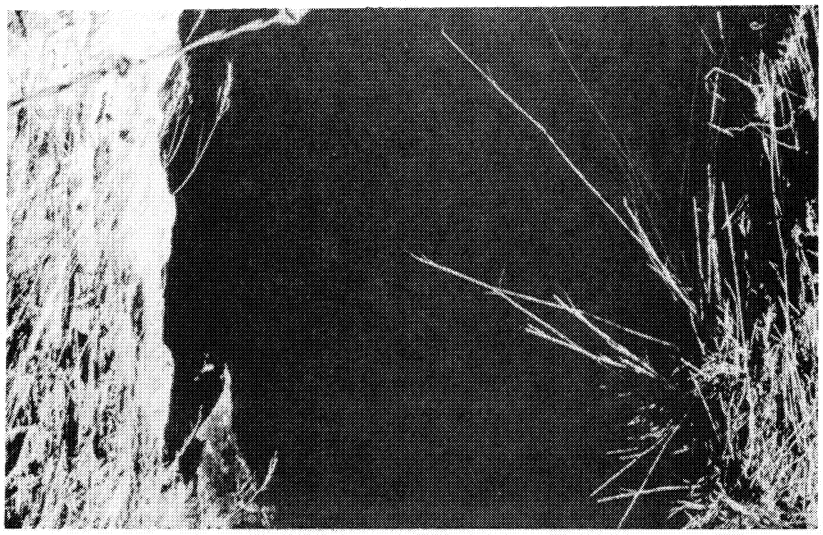

Figure 26. Close-up of a major pipe from previous figure.

Figure 27. Dark areas below center are piping inlets located approximately 10 feet behind the cut.

Figure 28. The drainage basin above the piping is relatively large. The lack of an adequate drainage system explains the extensive damage.

Figure 29. The natural surface drainage is away from the slope face. Little erosion damage has occurred.

Figure 30. Wind erosion near Washtucna.

instead of the benched cut designed with no form of erosion control present.

Although some provisions for controlling erosion were included in the original specifications, additional steps are needed. No reference was made to side ditches for the removal of excess runoff. While other transportation departments did not give guidelines as to when systems for conveying runoff of the slope should be installed, the previous photographs indicate that this may be necessary for relatively small drainages.

One of the major problems in designing runoff drainage systems in loess is determining the degree of channel protection necessary for a given gradient. Very few quantitative methods are presently available that are applicable to loess. One investigation that may prove useful was conducted by Keeley (18) and relates discharge and gradient to channel stability for various soil types. Although design charts were not developed specifically for loess, charts are available for silty clays and sandy silts which may be applicable.

Another serious erosional problem in loessial soils, more specifically on flattened slopes, is surface erosion during construction and up to the time of establishment of a good vegetative cover. Even with adequate drainage, extensive damage may result from raindrop impact and rill erosion. A number of publications provide useful information on controlling erosion of cut slopes during and after construction (10,16,26). In all cases surface protection, using either straw mulch or some type of synthetic material, is considered the primary method of reducing erosion on recently excavated slopes.

The ability of a slope to hold a vegetative cover appears to be closely related to the steepness of the slope. Unfortunately the relationship is complicated by factors such as exposure, type of vegetative cover, soil type and climatic conditions. As a result of these additional factors, no investigator to date has been able to develop a mathematical relationship, either theoretical or empirical, that accurately predicts the maximum angle a slope may be cut and still retain a continuous vegetative cover. Lacking a quantitative method of determining cut slope angles, many of the transportation departments contacted tend to flatten slopes to 2.5:1 or less, with generally positive results.

Shallow Downslope Movements

Shallow downslope movements were observed within the eastern one-third of the study area. This type of failure is largely due to late winter and early spring climatic conditions. It is common to get precipitation or snowmelt at this time of year, resulting in a thin layer of thawed, saturated soil overlying either frozen or unsaturated soil. The layer of thawed, saturated soil along with any overlying vegetation tends to slide or flow downslope.

The form in which this type of failure manifests itself within the study area appears to be primarily due to the amount of precipitation, clay content and slope angle. In the western two-thirds of the study area, where precipitation is less than 15 in. annually, shallow downslope movements were rarely observed. Additionally, clay content increases from west to east as does precipitation. Increases in clay content, resulting in lower permeability, combined with increased precipitation, raises the likelihood of obtaining the near surface saturated conditions required for failure.

Two different forms of this shallow slope failure have been observed and appear to be related to soil type. In silty loess it is not uncommon to see sheets of vegetative cover, 2 to 6 in. thick with an arcuate upper boundary, move downslope (Figure 32). In this form, only minor damage was observed with no cases of extensive degradation noted. However, over the years these small failures can expose a lot of soil to erosion.

In clayey loess shallow slides and flows are common and result in major slope degredation. Movement appears to be a mudflow phenomenon with both large and small scale failures observed. At least minor damage was observed in the many of clayey loess slopes over 10 ft. high.

Small scale slides and/or flows, such as in Figure 33 are the most common form of failure. Failures are typically 1 to 10 ft. wide with the depth of failure ranging between inches and 3 to 4 ft. In most cases the initial failure is followed by increased erosion due to the loss of vegetative cover with severe gulley erosion a common result. Observations in the spring of 1985 indicate that in some cases failure may be due to saturation of the soil under the snowpack as well as due to weight of the snowpack on underlying saturated slope (Figure 34).

Although not as common, large scale slides and/or flows have been observed. The failure mechanism is thought to be the same as for smaller scale failures with a low depth to width ratio for the failure surface. Figure 35 illustrates a relatively large failure. The effect of slope angle on shallow failures cannot be emphasized strongly enough. In all cases where extensive damage was observed, slopes were 2.0:1 or steeper. No instances of failure were observed for slopes flatter than 2.5:1. These observations agree with past investigators who found slopes greater than

Figure 31. Close-up of wind eroded slope illustrating ventifact-like faceting.

Figure 32. Shallow failures with arcuate scarps are fairly common in silty loess near the eastern extremity of the study area.

Figure 33. Small scale mudflow in highway cut on highway 195 (near Pullman, WA).

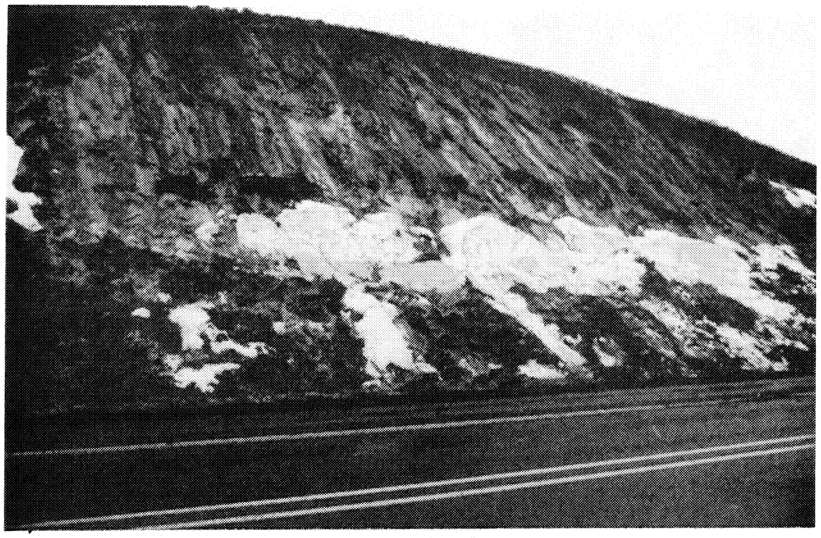

Figure 34. Failure of slope under melting snow drifts (near Pullman, WA).

Figure 35. Relatively large scale mudflow located near Pullman. Undisturbed soil to the right of the photograph indicates the depth of failure at approximately 3 feet.

2.5:1 too steep to maintain good vegetative cover in loessial soils (25,31).

Exposure definitely has an influence on these shallow slides and flows. It is not uncommon to find two opposing cuts with similar slopes and drainage, one facing north and the other south, to exhibit extremely different performance. The north facing slope will invariably demonstrate a greater degree of degradation due to shallow slides and flows than the south facing slope. This is not surprising as slopes facing to the north typically have higher average water contents than any other orientation. Figures 36 and 37 show south and north facing slopes (respectively) cut in clayey loess at approximately 2:1. Note in Figure 36 that some erosion has occurred where small patches of vegetation and soil have slipped away. However, the north facing slope (Figure 37) has experienced numerous shallow failures which have stripped the vegetation. Obscured by the snow drift are scarps from larger failures, which have occurred over the past several years, that have significantly steepened the crest of the slope. The result of the shallow slides is exposure of bare soil and rapid formation of erosion gulleys, some of which range up to 2 ft. in depth (Figure 37).

The practice of constructing drainage ditches immediately below the toe of slopes appears to contribute to this type of failure. Periodic highway maintenance requires removal of sediment from the ditches which may result in undercutting the toe. Additionally, drainage ditches directly adjacent to the toe often raises the water content, further encouraging failure conditions. This problem may be reduced by placement of drainage ditches 10 to 15 ft. away from the toe of the slope.

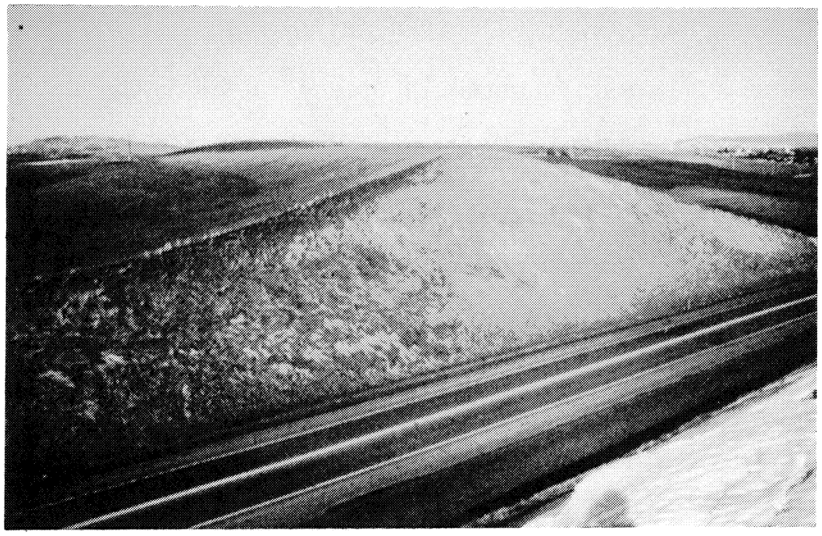

Figure 36. South facing slope shows little degredation (Pullman, WA).

Figure 37. North facing slope opposite the cut in Figure 36 exhibits severe gulley erosion.

Rotational Failures

Although no rotational failures were observed during the field study, other investigators have reported encountering such failures in the past (14,23). These failures occurred in clayey loess in the extreme eastern section of the study area. Failures of this type have taken place primarily during the spring when soils were at or near saturation. The reason rotational failure surfaces are so limited may be due to the fact that loessial soils generally do not reach saturation at depths much greater than 2 or 3 ft. Although complete saturation is not a requirement for producing a rotational failure in loess, it is likely that near saturated conditions are necessary to reduce strength sufficiently to produce a deep seated failure of any geometry.

PRELIMINARY DESIGN AND MAINTENANCE RECOMMENDATIONS

Preliminary results from the field study and laboratory testing indicate that southeastern Washington loess is very similar to deposits found in the central United States. Consequently, design guidelines utilized by transportation departments for midwestern loessial deposits can be adapted for local use. Adoption of the following recommendations should improve slope performance; however, some experimentation in use of slope angles, drainage ditch liners, etc. is recommended to optimize design.

Field and Laboratory Investigation

Any new highway construction or major realignment project must include a field investigation. As a minimum, a sufficient number of down-hole samples should be obtained to establish general trends and values of natural water content as well as the gradation characteristics of the loess for that particular location.

When either deep cuts (>50 ft.) are required, or water contents approach saturation, it may be necessary to collect undisturbed samples for strength testing. When ground water conditions are such that achieving a saturated condition is considered unlikely, a total stress analysis is the preferable approach. Conversely, where water contents in excess of critical (as defined previously) may be anticipated, effective stress analysis on saturated samples should offer the best results.

The failure surface to be used for a slope stability analysis is not easily defined. In silty and sandy loess no major slope failures were observed, and in general slope stability is not a problem. Failures in clayey loess are primarily shallow slides or flows.

If a slope stability analysis is to be performed on a silty loess maintaining water contents below critical, a wedge failure is perhaps the most likely geometry. In such a situation the analysis should be based on total stress parameters.

The shallow slides or flows commonly observed in clayey loess are probably best modeled by an infinite slope analysis. The thin, saturated zone near the surface can be conceptualized as relatively weak soil with the underlying unsaturated or frozen ground representing a stronger soil. The analysis should be based on effective strength parameters for the saturated layer, possibly with seepage forces incorporated into the solution.

When saturation at depth is encountered for either silty or clayey loess, some sort of rotational failure may occur; although, due to possible anisotropy of the soils the geometry of the failure surface may not be circular in nature. However, since the actual failure geometry is not known, a circular failure surface may provide the closest approximation possible. The slope analysis should be based on effective stress parameters.

Vertical Versus Flattened Slopes

If the soil at the site of the proposed cut is a silty loess with water content below critical, vertical cuts may be considered. If vertical cuts are utilized, they should be benched on approximately 20 ft. vertical intervals when the total height of the cut exceeds 25-30 ft. Benches should be 15-20 ft. wide and gently sloped toward the back of the cut. If either water content exceeds critical (17% can be used as an approximation based on experience in the midwest) or the soil is a clayey loess, flattened slopes should be utilized. Generally 2.5:1 slopes should perform adequately, but if a water table is intercepted, flatter slopes may be required due to seepage forces. Although design criteria have not been developed for sandy loess, it is felt that clay content would be so low that vertical cuts would perform poorly.

Erosion Control

Erosion control practices similar to those reported by Royster (30) are suggested for Washington loess. With the possible exception of short excavations through small lobate ridges of loess, a drainage ditch approximately 10 to 15 ft. behind the top of the cut should be constructed before the slope cut is made. The ditch should be seeded or lined, depending on the gradient. The drainage ditch should be constructed prior to opening of the cut with as little disturbance to the surrounding vegetation as possible. Once the cut is made construction equipment should be kept away from the crest. If natural drainage channels are truncated by a cut, the drainage system should be adequate to transmit the flow around or over the cut face in protected channels or pipes.

Standard farming techniques entail cultivating to the edge of road cuts. This practice is not acceptable if the ditches above the slope crest are to remain operable. Continued cultivation over a drainage ditch will ultimately destroy its effectiveness. Therefore, the most desirable location for the drainage ditch would be within a protected right-of-way.

It is suggested that for new construction drainage ditches should be constructed approximately 10 ft. away from the toe of the slope, and the ground surface should be gently sloped toward the ditch. Any material that spalls downslope between the toe and the ditch should be left in place.

In cases where benched cuts are required, the benches should be seeded or sodded. If the upper drainage system is properly constructed it should not be necessary to employ ditches on the benches, or use erosion control methods in excess of vegetative cover unless extremely long cuts are made.

Side ditches offer some of the most severe erosion problems. Gradients are generally steeper than along the cut and flows tend to be higher due to the concentration from various sources. In many cases it has been necessary to pave ditches or use halved culverts to prevent erosion. It is suggested that WSDOT experiment with sodding, synthetic liners, etc. to establish the optimum design.

If a flattened slope is constructed, the cut should be seeded immediately following construction. In addition, a protective cover should be placed over the slope, either a straw mulch or some type of synthetic material. These covers serve the dual purpose of preventing raindrop erosion, a major cause of erosion on newly opened cuts, and help retain moisture required to initiate a vegetative cover.

Periodic Maintenance

Due to its highly erosive nature, loess slopes will deteriorate very rapidly once erosion is initiated. Thus it is very important to repair any erosion damage as soon as it is discovered. Maintenance may require repairs to, enlargement of, and removal of siltation from existing ditches. Increased erosion protection, such as installation of liners or filters in ditches, or in some cases construction of drainage facilities where they were previously believed to be unnecessary may be required.

Vegetative cover requires periodic attention. In order to maintain a heavy ground cover, fertilizer must be applied every 3 to 5 years (based on midwest experience). In addition, some areas will not seed well the first time and may require a second and possibly third seeding.

Removal of sediment from toe ditches on existing slopes should be done carefully to avoid undercutting of the toe of the slope. Even minor undercutting will cause at least some sloughing, and therefore the grader blade should not contact the slope cut.

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APPENDIX

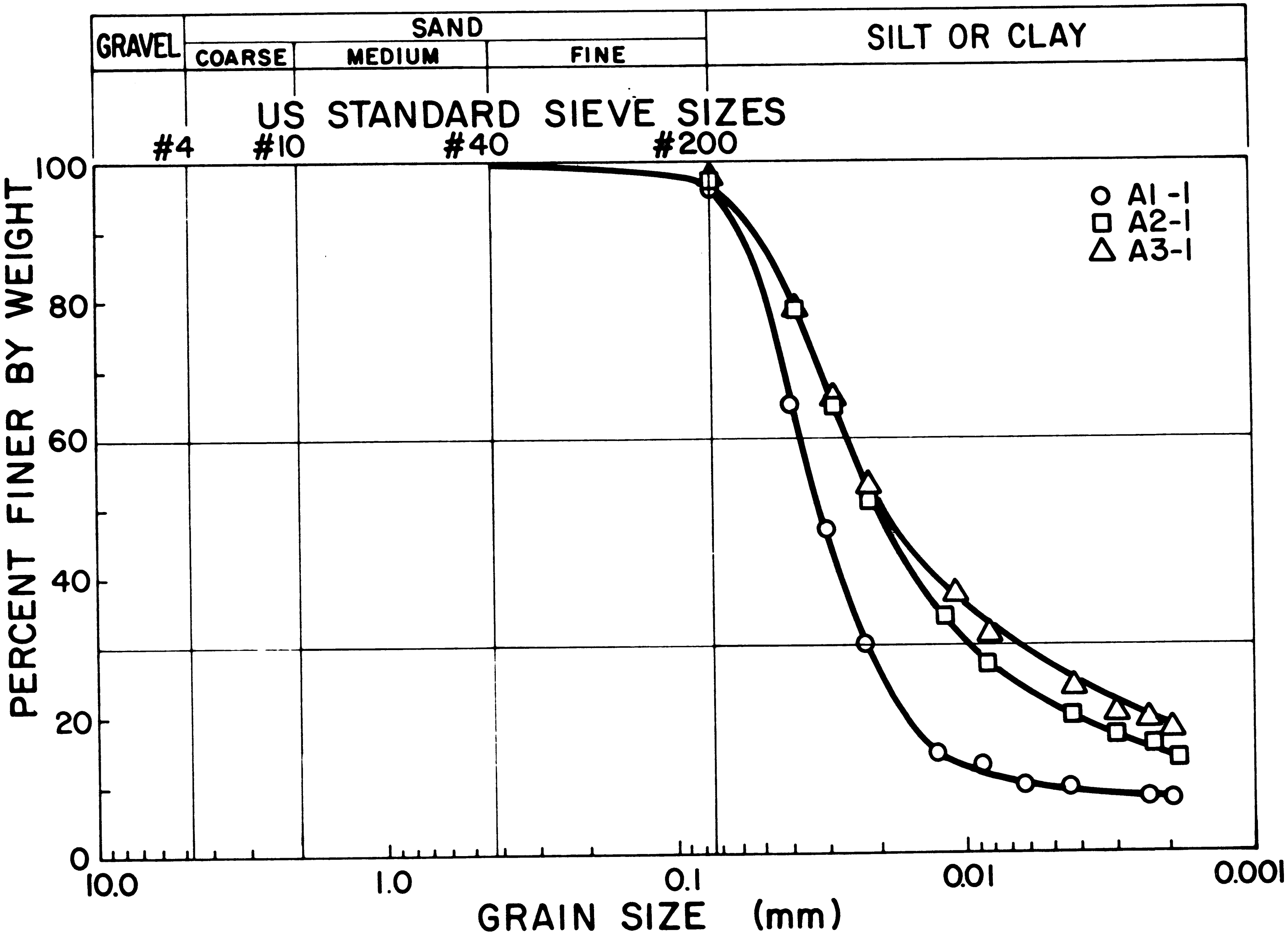

Figure 38. Gradation curves for samples A1-1, A2-1, and A3-1.

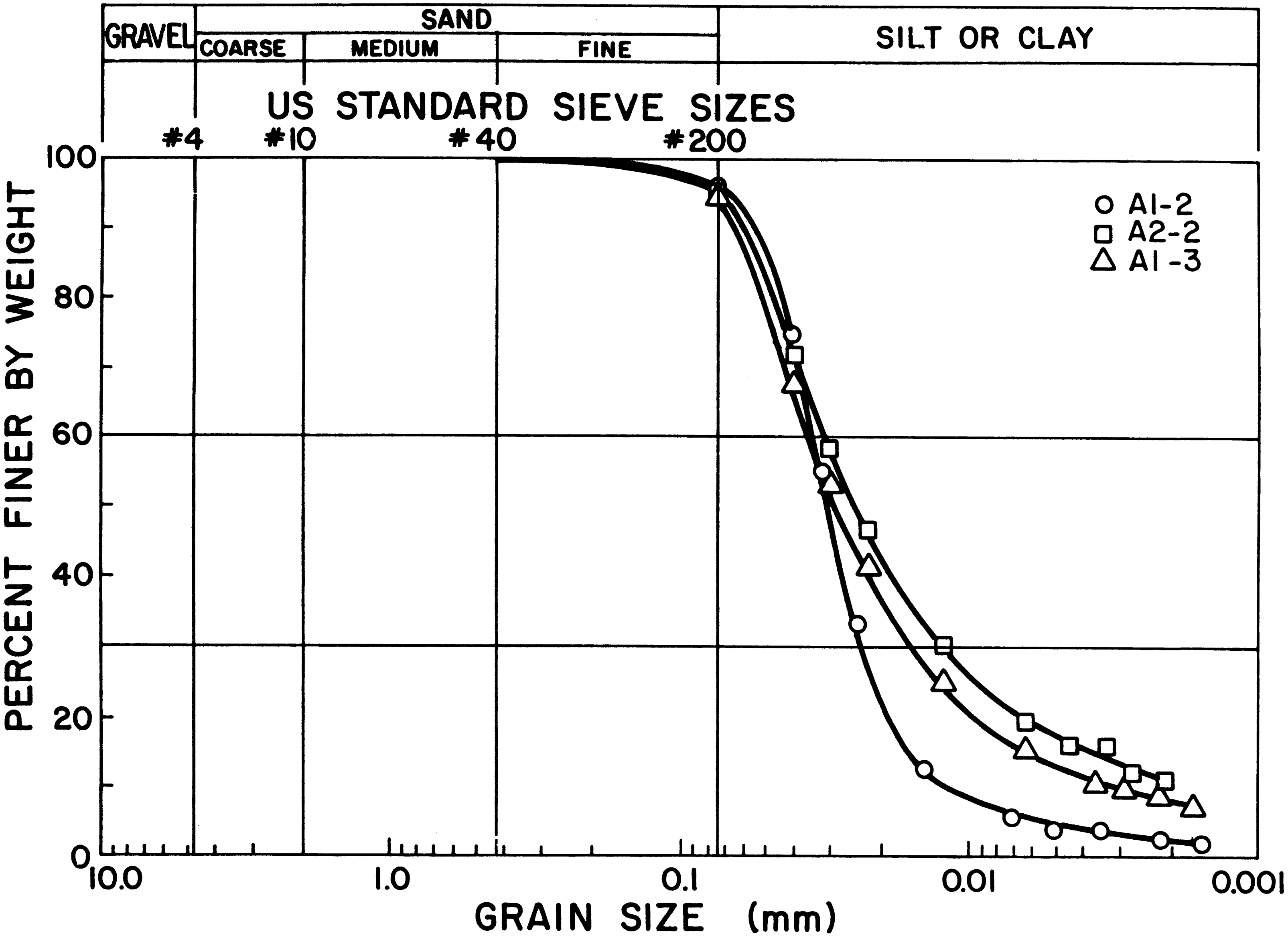

Figure 39. Gradation curves for samples A1-2, A2-2, and A1-3.

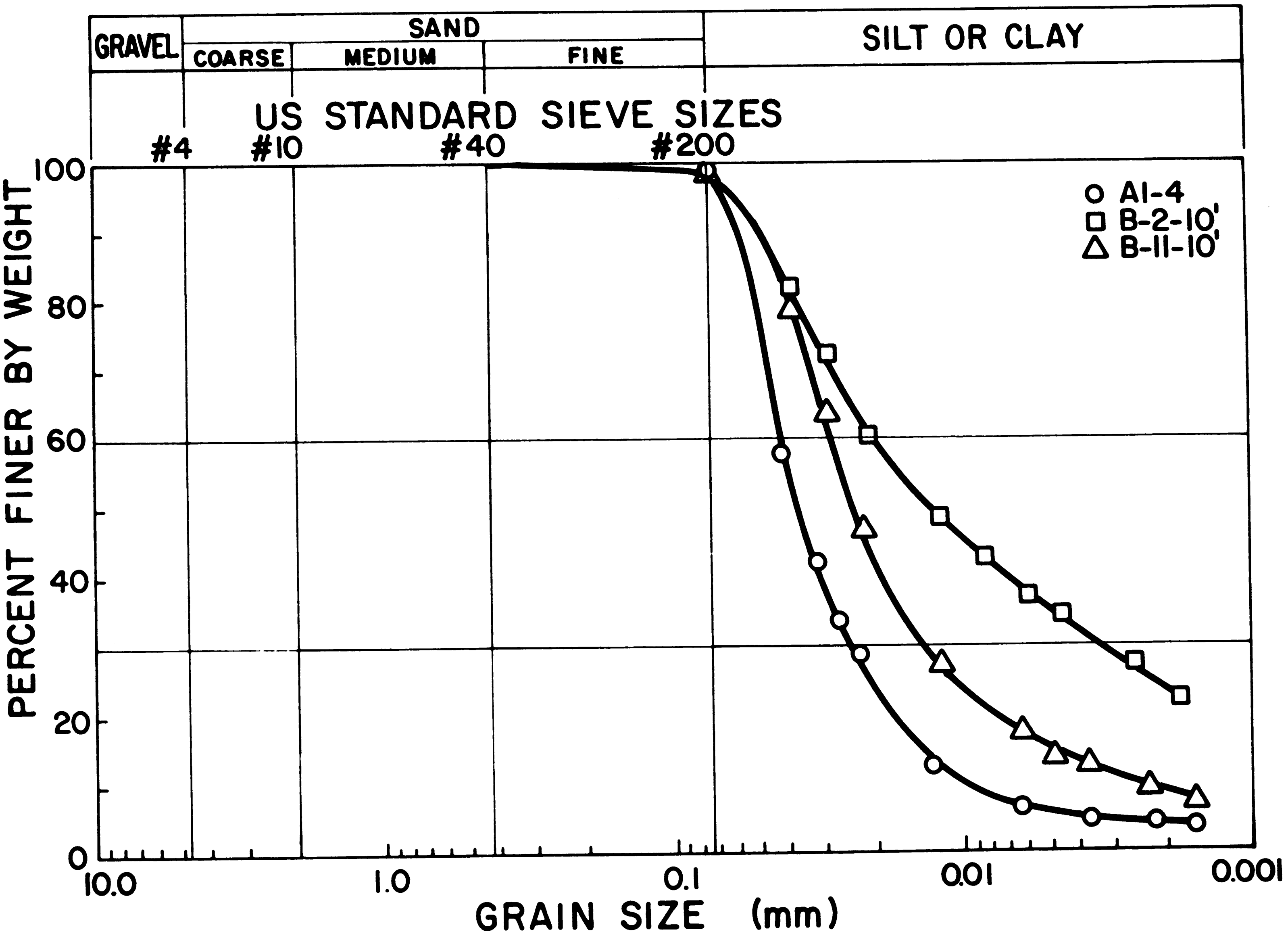

Figure 40. Gradation curves for samples A1-4, B-2-10', and B-11-10'.

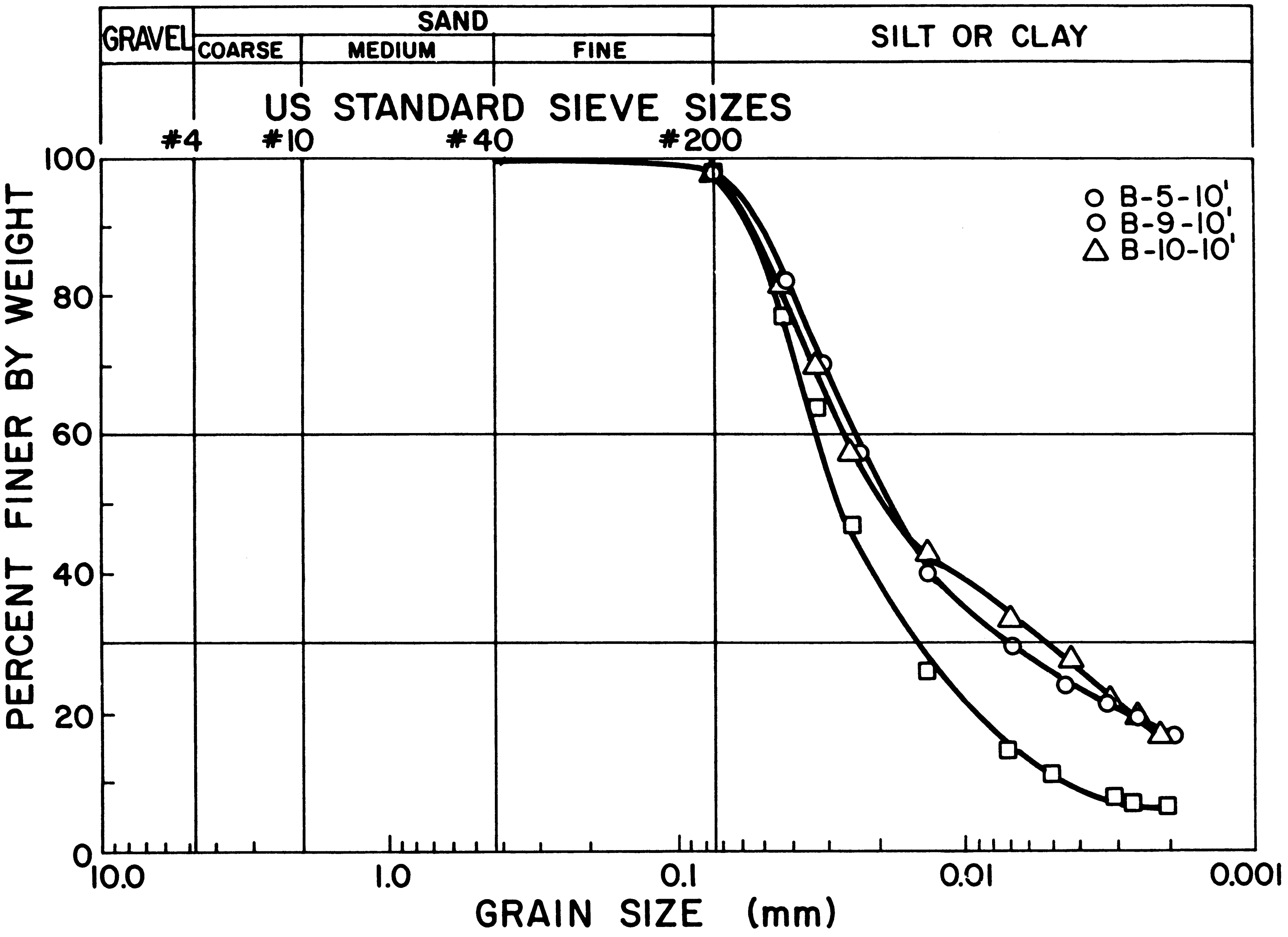

Figure 41. Gradation curves for samples B-5-10', B-9-10', and B-10-10'.

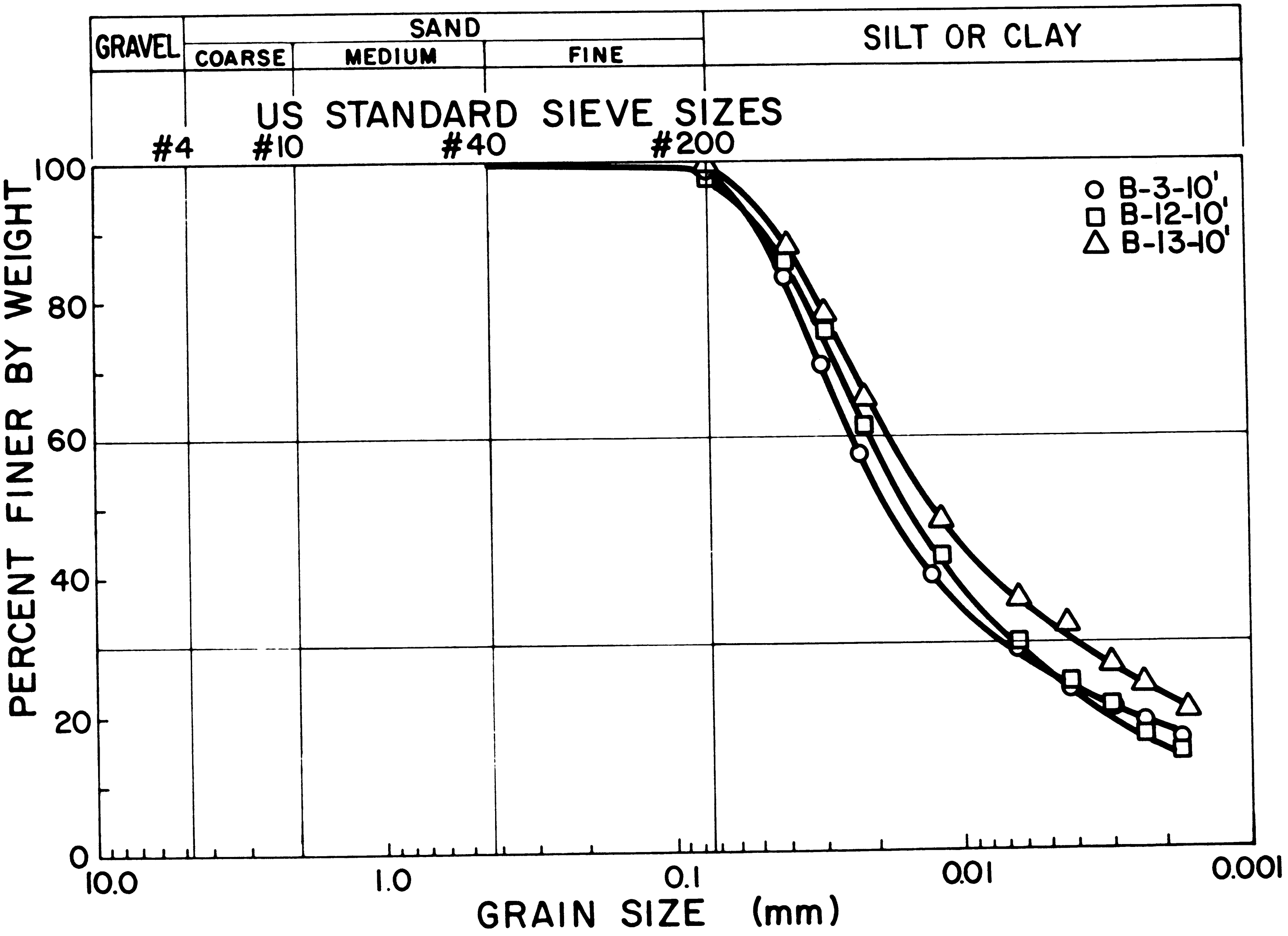

Figure 42. Gradation curves for samples B-3-10', B-12-10', and B-13-10'.

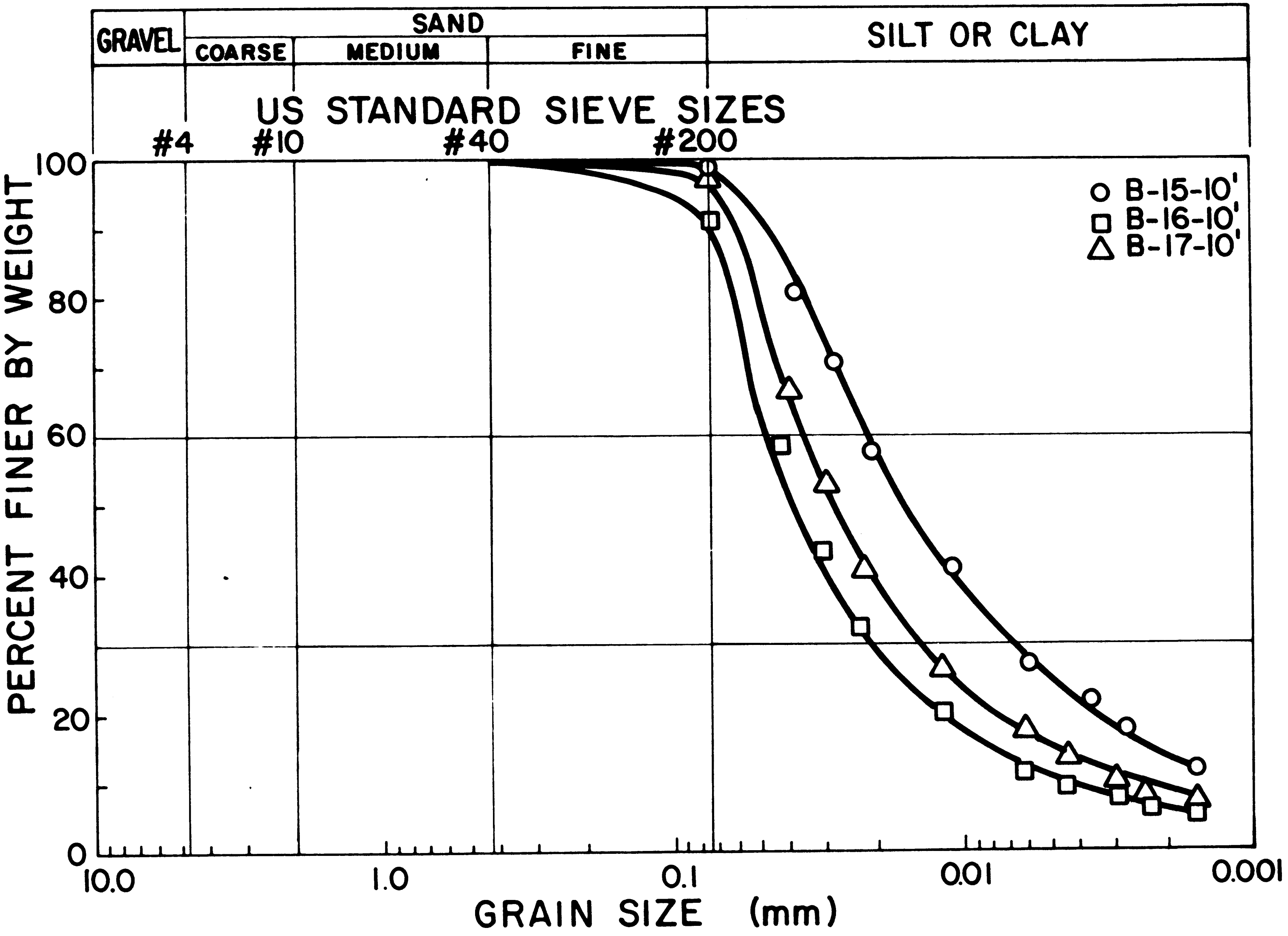

Figure 43. Gradation curves for samples B-15-10', B-16-10', and B-17-10'.

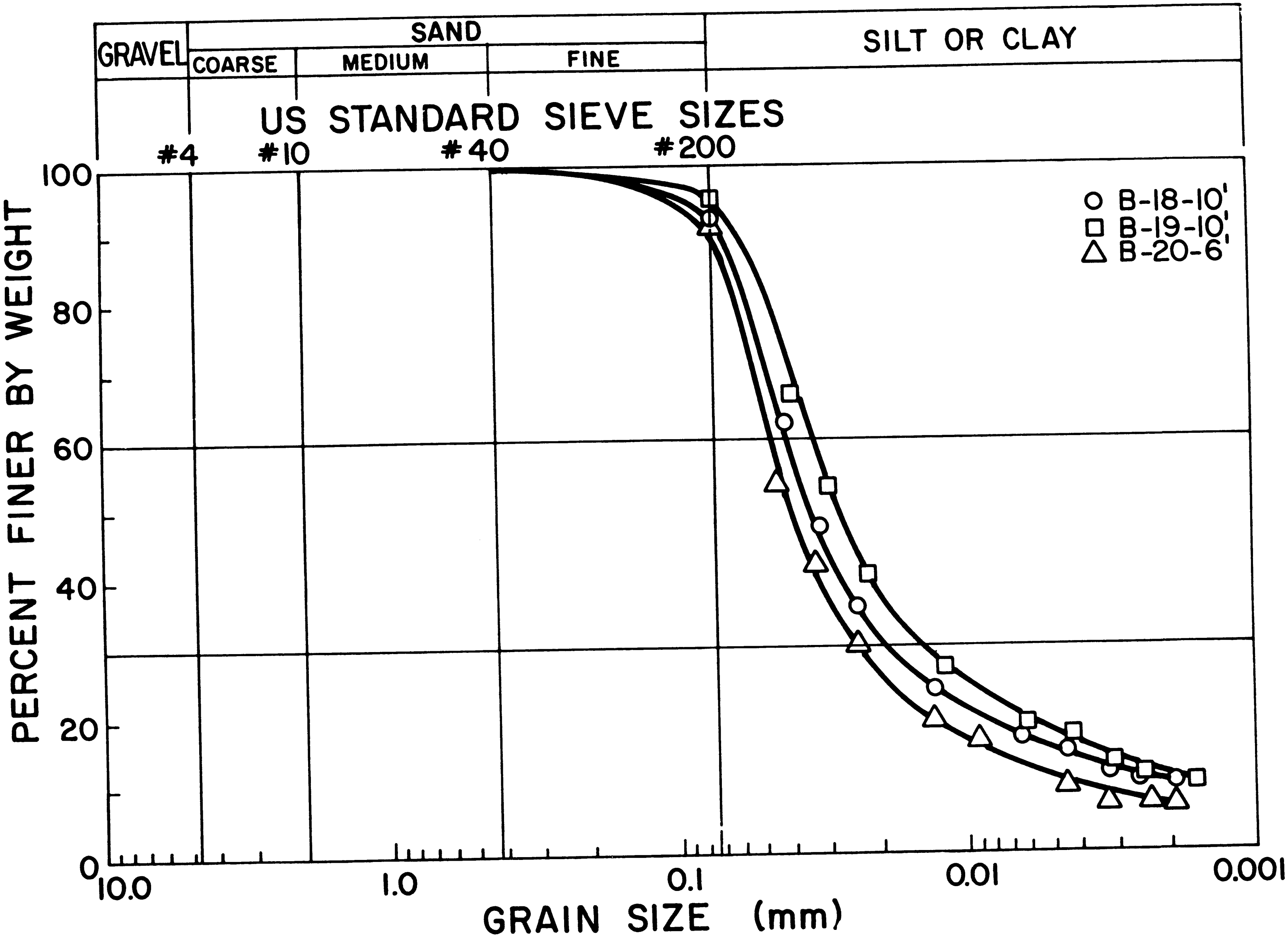

Figure 44. Gradation curves for samples B-18-10', B-19-10', and B-20-6'.

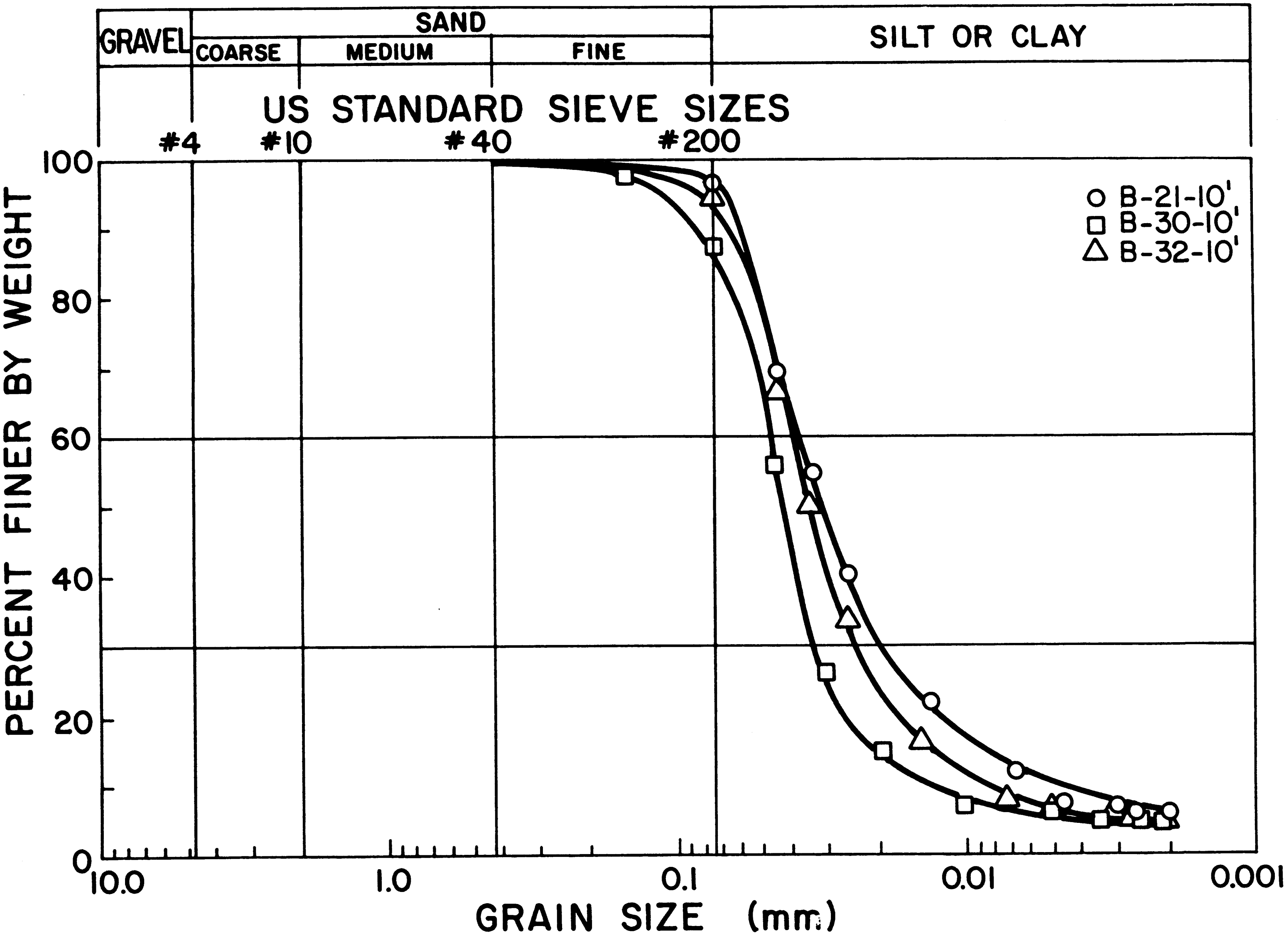

Figure 45. Gradation curves for samples B-21-20', B-30-10', and B-32-10'.

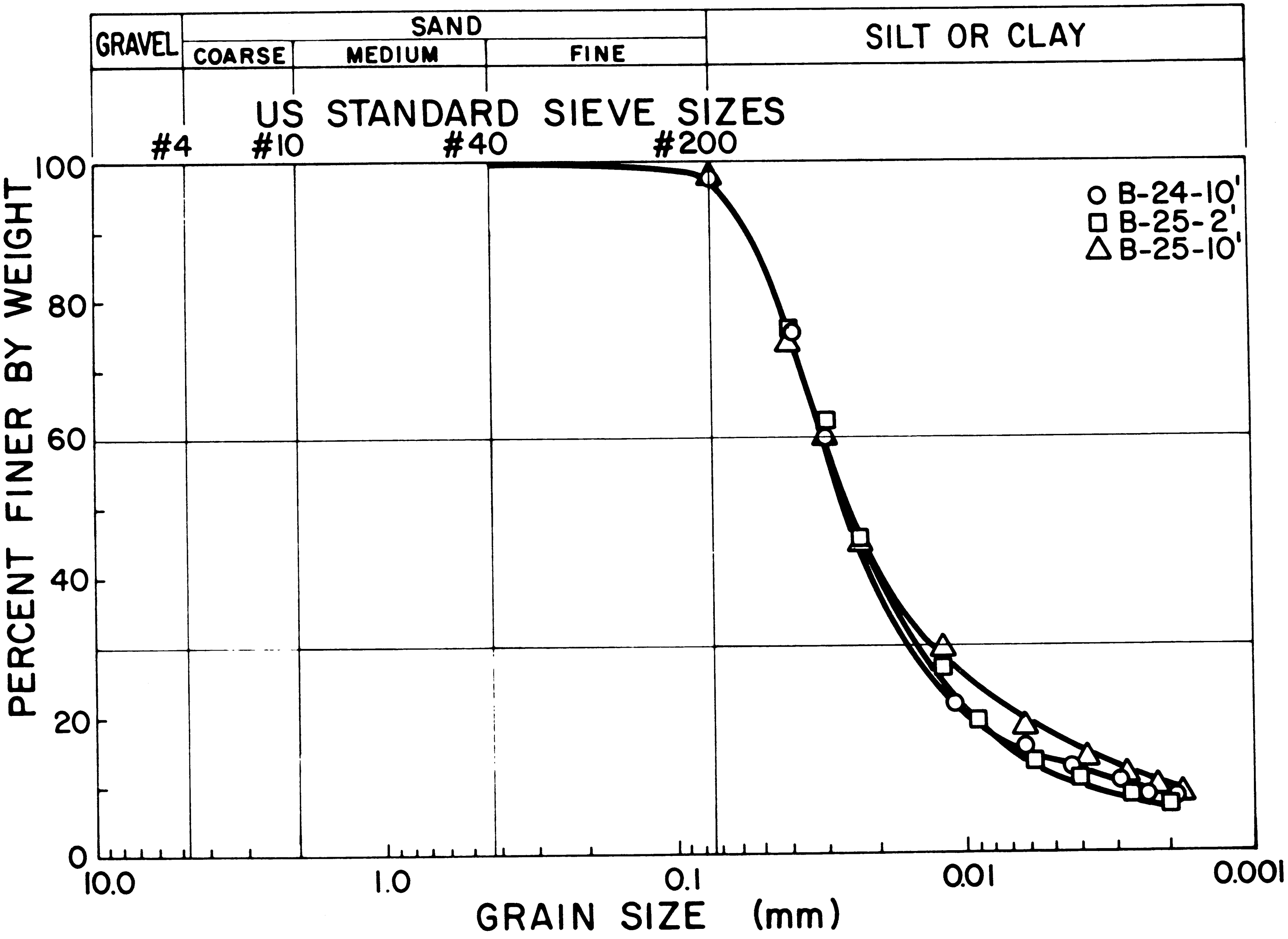

Figure 46. Gradation curves for samples B-24-10', B-25-2', and B-25-10'.

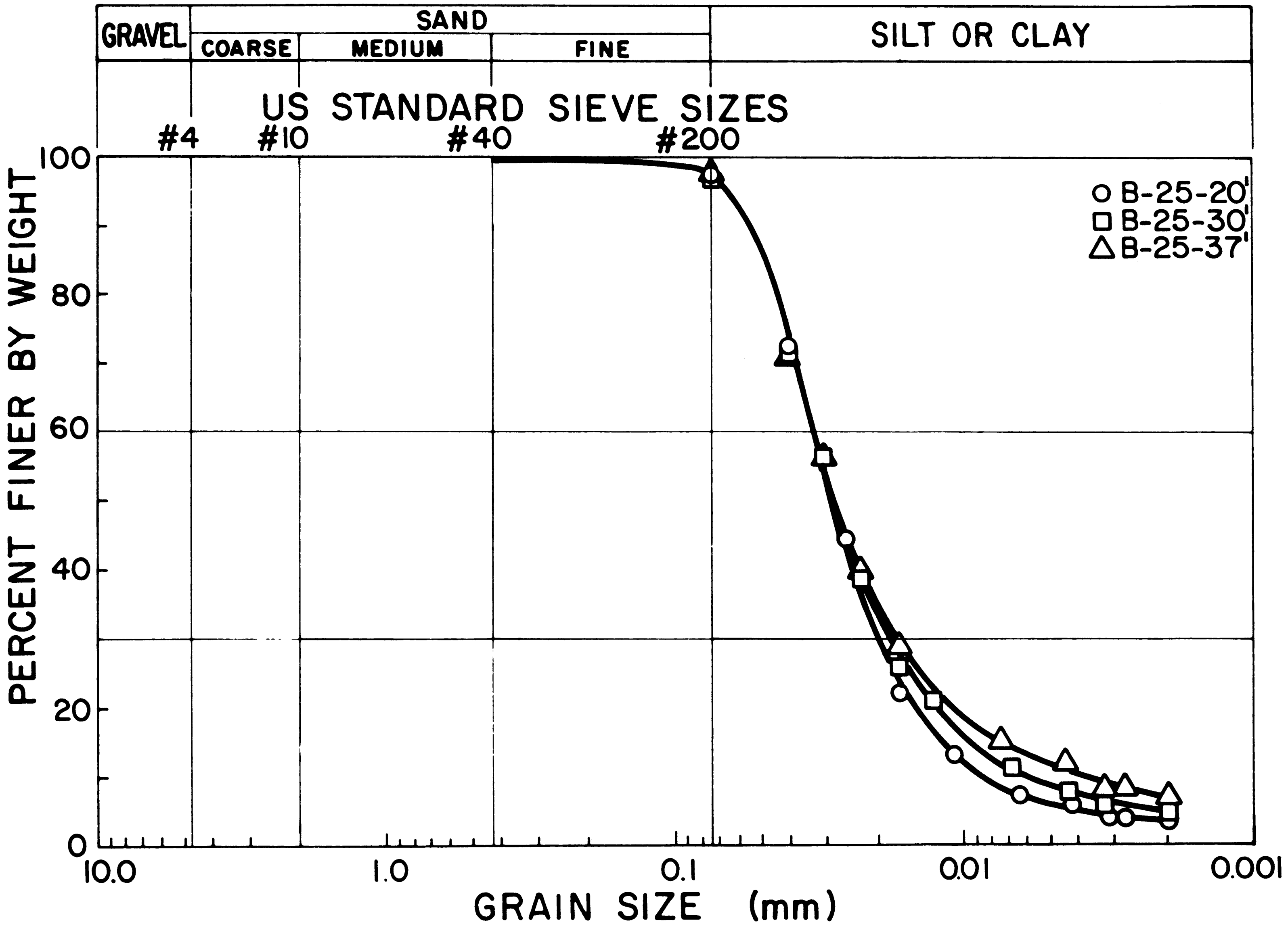

Figure 47. Gradation curves for samples B-25-20', B-25-30', and B-25-37'.

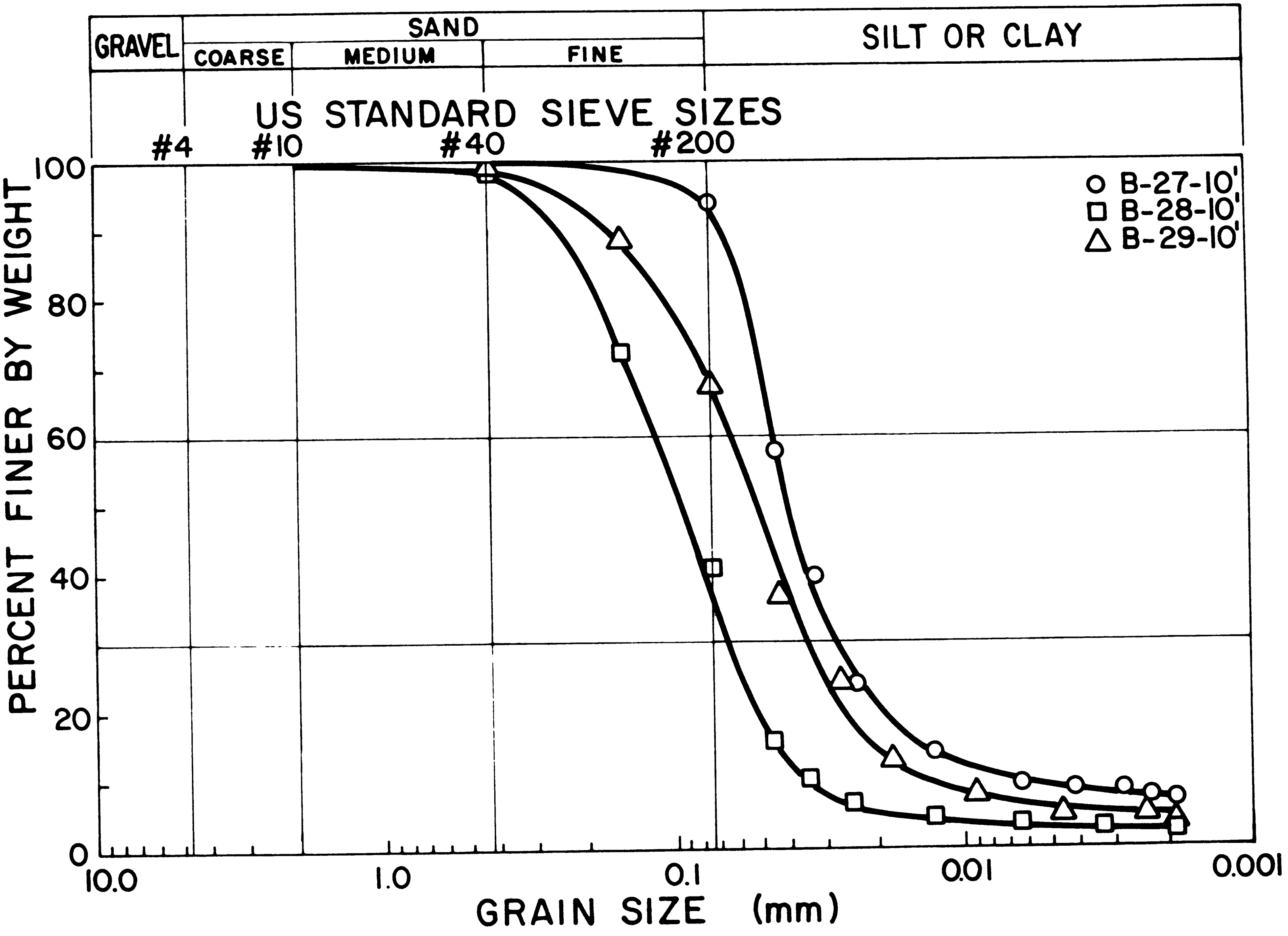

Figure 48. Gradation curves for samples B-27-10', B-28-10', and B-29-10'.

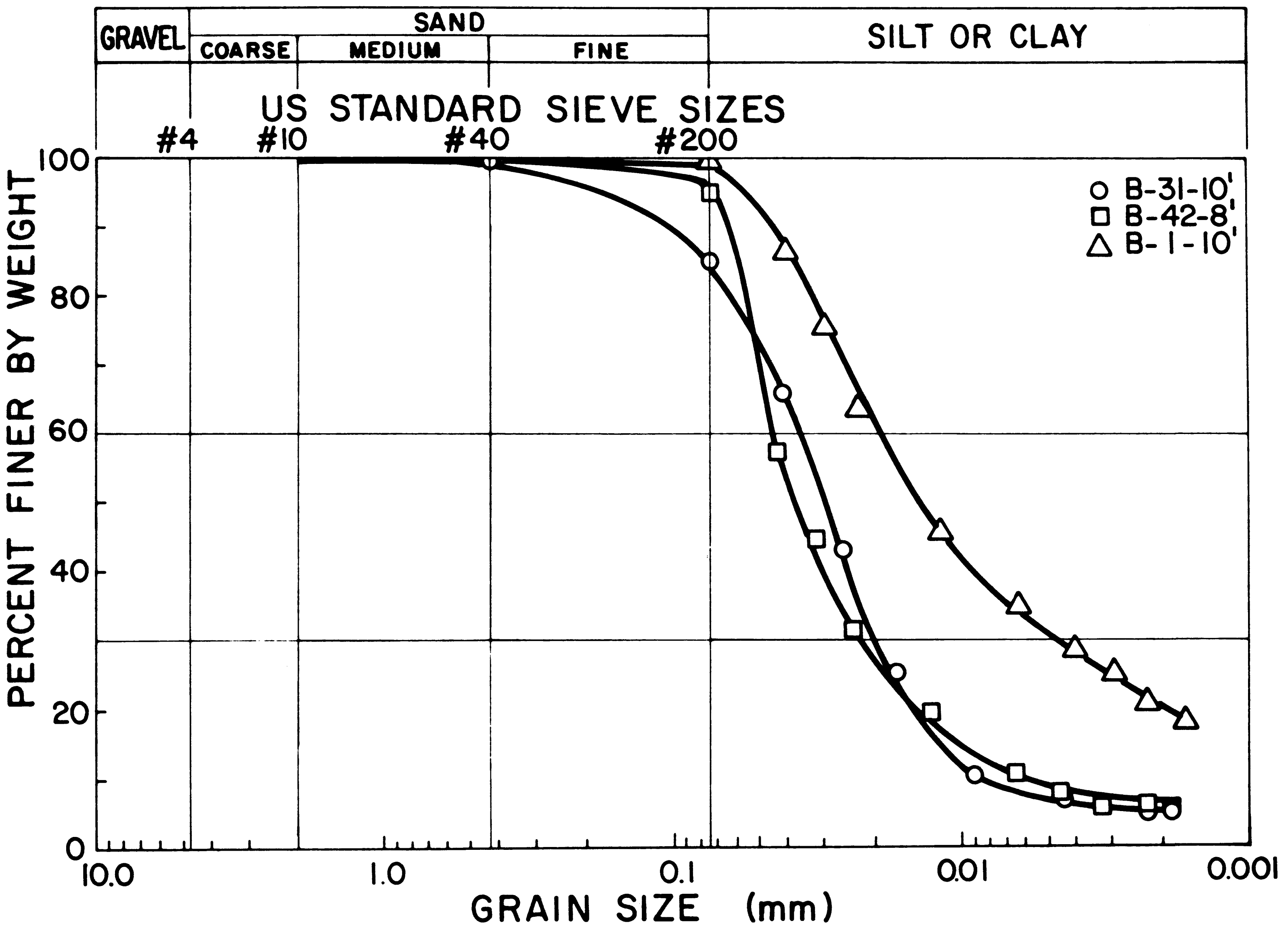

Figure 49. Gradation curves for samples B-31-10', B-42-8', and B-1-10'.

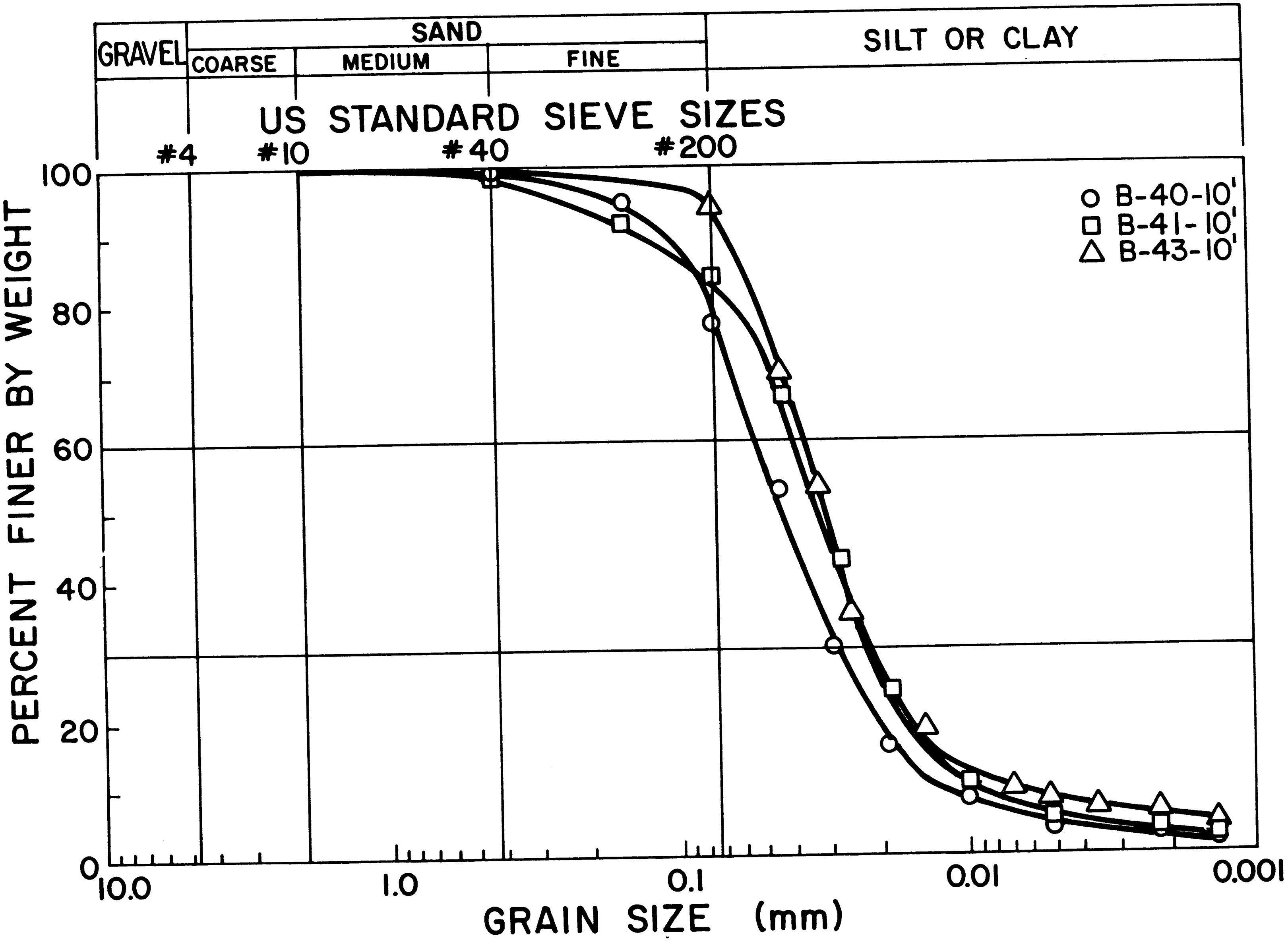

Figure 50. Gradation curves for samples B-40-10', B-41-20', and B-43-10'.

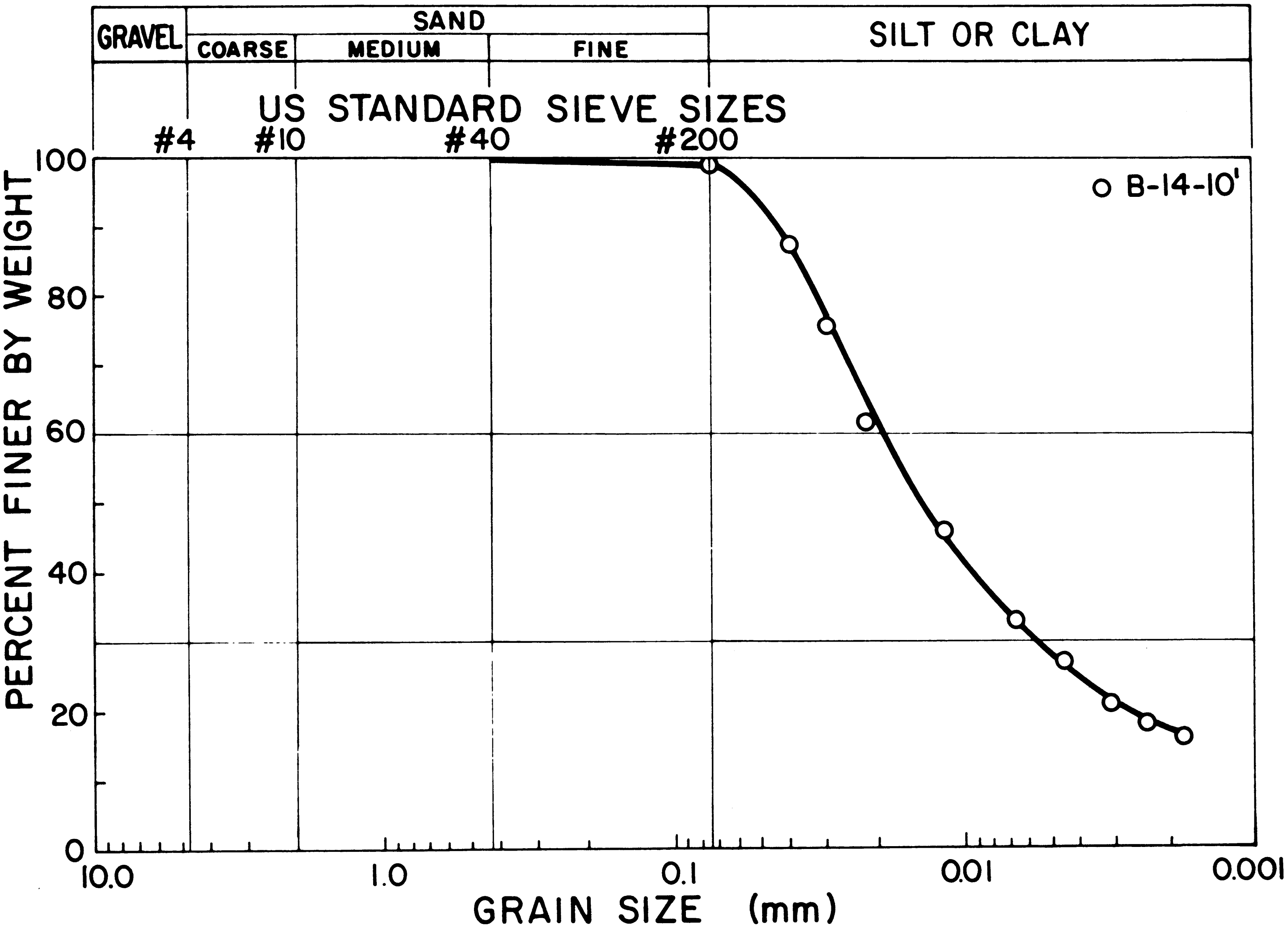

Figure 51. Gradation curve for sample B-14-10'.