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PRELIMINARY PROCEDURAL GUIDE FOR ESTIMATING WATER AND SEDIMENT YIELD FROM ROADS IN FOREST

PREPARED FOR

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According to the study plan, this report on the preliminary procedural guide for estimating water and sediment yield from roads in forest is submitted.

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I. INTRODUCTION

It has long been recognized that roads are the primary sources of accelerated erosion and sedimentation from forest watersheds. Significant quantities of sediment delivered to the channels may cause adverse impacts on aquatic and riparian systems, reduce channel capacity, and increase flood hazards. A properly built and maintained road with adequate sediment control can effectively reduce sediment yields and decrease erosion impacts on the downstream channels.

The evaluation of alternative routes and alternative designs of road cross sections, road gradients and surfaces, cut slopes, embankments, and spacings of cross drains requires a method to predict sediment yields from various roads. In addition, the prediction of water and sediment discharges is necessary for determining sediment control measures either within the buffer strip between road and stream or in channels.

Because the physical processes governing erosion from roads are very complicated, many past studies have utilized a statistical interpretation of observed erosion data. The Universal Soil-loss Equation developed by Agricultural Research Service is an example of these studies. However, it is difficult to predict the erosion rate associated with various design alternatives using statistical methods because the methods are based on the assumption of homogeneity in time and space. In spite of the complexity of the physical processes governing soil erosion, numerical modeling of the process systems is likely the most viable way to estimate the time dependent and space dependent (change with design alternatives) sediment yield from roads.

Research to meet the above-mentioned needs has resulted in formulating of a numerical physical process model that simulates surface erosion from roads (Simons et al. 1976). Many processes in this road sediment model are similar to those in the watershed surface erosion model (Simons et al. 1975), such as raindrop soil detachment, infiltration, overland surface flow routing and sediment transport. In the road sediment model, however, there is no vegetation cover and channel routing takes place in ditches and culverts. This model has not been validated because of lacking field data. Because the complexity of this numerical model may curtail practical applications, a simplified solution which approximates the complicated numerical solution is appealing. Outgrowths from development of the road sediment model have been the generation of a preliminary procedural guide consisting of a series of graphs. This report describes its development, limitations, and examples of applications. These graphs were generated utilizing the road sediment model in accordance with some assumptions required for simplification. The graphs relate such variables as rainfall intensity, storm duration, infiltration rate, soil detachment rate, sediment size, ground cover conditions, road gradient, cut and fill slope, sediment discharge and water discharge. These generated graphs can be used by the forest planner or engineer to quickly estimate water and sediment yield from roadways of different designs. Because both the road sediment model and the procedural guide have not been validated in any field condition, the present procedural guide can only be applied qualitatively. This guide can be used for assessing relative quantities of sediment yield from surface erosion on roads considering alternate route locations, cross sections, road gradients, types of surfacing, and spacings of cross drains. This method is useful in selecting the design alternative which produces the least sediment rather than determining how much sediment would be produced.

II. PROCEDURAL GUIDE

This chapter will describe the main factors controlling surface erosion from roads, the structure of the road sediment model developed by Simons et al. (1976), and the development and limitation of the preliminary procedural guide for estimating water and sediment yields from roads.

Factors Controlling Surface Erosion

Soil erosion is the detachment and subsequent movement of soil particles in an entraining medium. Road erosion is usually categorized into sheet and rill erosion components.

In general, erosion rates vary with climate, soil, vegetation, topography, and land management. Erosion from roads is a function of (1) direct rainfall or snowmelt; (2) soil type and geology, (3) topography and route locations, such as road gradient, and (4) road designs, such as road cross section, cut or fill areas, sand surface, spacing of cross drains, and other sediment control measures.

A comprehensive evaluation of the importance of factors controlling road surface erosion has been conducted by the personnel from National Forest Service Region 5 and 6. It was concluded from the evaluation that the following factors are very important or at least important for controlling surface erosion from roads in forests: (1) slope angle prior to road construction, (2) cut slope length and angle, (3) fill slope length and angle, (4) road bed gradient, (5) longitudinal ditch gradient, (6) cross drain spacing and size, (7) soil data including saturated hydraulic conductivity, average capillary suction pressure, soil porosity, degree of saturation in the wetted zone, and particle size distribution for road bed surface, cut slope and fill slope, (8) vegetative type, cover density above the road cut, below the road fill, on the cut and fill slopes, (9) ground cover density above the road cut, below the road fill, on the road bed, cut slope and fill slope, and (10) climatic data such as rainfall intensity, duration, and snowmelt rate.

Structure of Road Sediment Model

The road sediment model developed by Simons et al. (1976) was formulated according to the physical principles of water flow and soil erosion processes. This model mathematically represents in a set of equations the physical processes of erosion by raindrop impact and running water and the movement of water and sediment from watershed onto and along the road, into and through the ditches and cross drains, and back onto the watershed. These equations were solved by numerical techniques to give the amounts of water and sediment at any location along the road at any time. The schematic structure of this initial model is shown in Fig. 1. A brief summary of the primary processes is given below.

Infiltration: This component of the model simulates the process of infiltration. The infiltration rate is computed by an approximation of Darcy's Law assuming that a distinct wetting front exists and it is formulated to be a function of saturated hydraulic conductivity, average capillary suction pressure, soil porosity, antecedent moisture content, and moisture content in the wetted zone. The rate of rainfall excess can thus be determined from the rainfall and infiltration rates.

Overland Surface Water Routing: With this component the overland surface water runoff on the road bed, cut slope and fill slope resulting from the rainfall excess is routed to other surfaces or ditches. The routing procedure is based on the continuity of water, a momentum equation of kinematic wave approximation, and a set of resistance functions for different hydraulic and ground cover conditions. The total resistance to flow is assumed to be a sum of the drag resistance due to ground cover and the shear stress acting on the soil bed. The computation is carried out utilizing a non-linear finite difference scheme developed by Li et al. (1975) and the computation results include the mean flow depth, total and effective bed shear stress and flow discharge at computation points as a function of time and space.

Overland Flow Sediment: This component of the model computes the amount of soil detachment by raindrop splash and by overland flow, the amount of loose soil pickup and transport by surface runoff, and bed-material load movement. Unlike the watershed surface erosion model developed by Simons et al. (1975), this model considers the routing of different sizes of sediment (more than two sizes). No specific differentation between wash load and bed material load is necessary. The amount of soil detachment by raindrop splash is assumed to be a simple power function of rainfall intensity. It is assumed that the amount of soil detachment by raindrop splash is negligible if the soil surface is covered by coarser soil material or a thin layer of water thicker than three raindrop size (see Mutchler and Young, 1975) that provides an armoring effect. The soil detachment by surface runoff is considered as the result of spatially increasing transport rates. The local transporting capacity of sediment is assumed to be a function of local effective bed shear stress, a combination of Meyer-Peter-Muller bed load equation (1960) and the Einstein suspended load procedure (1950) used as the sediment transport equation. The sediment routing procedure is primarily based on the continuity equation for sediment using a finite difference approximation and the coupling with the overland surface water routing procedure.

Ditch Flow Water Routing: This component of the model routes the water down the ditches in the road system and computes the hydrograph at the end of ditch outlet. The lateral water inflows to the ditch are the overland surface water flows. The ditch flow water routing procedure and the finite difference scheme are similar to those used in the overland flow water routing.

Ditch Flow Sediment Routing: With this component, the sediment is routed through the ditch system. The computation results include the sediment hydrographs, the amount of loose soil storage, and the amount of degradation and aggradation. The lateral sediment inflows to the ditch are the overland surface sediment flows. This sediment routing procedure is again similar to those used in the overland flow sediment routing.

Culvert Flow Water and Sediment: This component of the model routes water and sediment through the culvert. The routing procedure for both water and sediment are similar to those used in the overland and ditch flow. The main differences are: (1) no water and sediment lateral inflow, and (2) no sediment detachment by either raindrop splash or runoff. In order to simplify the complicated problems which may occur in the culvert flow, it is assumed that the design of culverts should be adequate for safe conveyance of water and sediment through the culvert. This component of model first determines the water and sediment transport capacity. If either the water or the sediment inflow rate is greater than the transport capacity, a message of "under design of the culvert" would be indicated. The water transport capacity is computed by utilizing Manning's equation and the sediment transport capacity is determined using the equation developed by Graf and Acaroglu (1968).

Preliminary Procedural Guide

The following preliminary procedural guide is developed utilizing the above-mentioned road sediment model in accordance with some assumptions required for simplification.

Assumptions: In order to develop this simplified procedure the following assumptions are made: (1) the design storms can be represented by a constant intensity and duration, (2) the flow reachs maximum discharge instantaneously, (3) the sediment yield can be approximated by examining the overall sediment availability during storm and the total sediment transport capacity for the whole runoff period and (4) armoring effect of water layer and loose soil is negligible. In general, these assumptions will yield a conservative estimation of sediment and water yields from roads.

Types and Ranges of Factors Considered: The governing factors considered in the procedural guide were determined by the sensitivity analysis utilizing the road sediment model and the consultation with the personnel from National Forest Service Region 5, 6, and 8. The factors considered are rainfall intensity, storm duration, surface water ponding time, infiltration rate, soil detachment rate, sediment size, ground cover conditions, cross drain spacing, area, ditch and culvert size, road gradient, cut and fill slope, sediment discharge and water discharge. After consultation with the personnel from National Forest Service Region 5, 6, and 8, it was decided that the ranges of key design factors considered in this preliminary procedural guide are as follows: (1) road bed gradients from 0.01 to 0.15, (2) cut and fill slopes from 1:1 to 5:1 (horizontal to vertical), (3) V-slope ditches with slopes from 0.02 to 0.12, (4) culvert sizes from 18 inches to 84 inches, (5) rainfall intensities from 1 inch per hour to 15 inches per hour, (6) soil types for infiltration determination cover clay, silt, fine sand and medium sand, (7) sediment sizes for transport rate determination include clay and silt (0.02 mm), very fine sand (0.1 mm), fine sand (0.2 mm), medium sand (0.4 mm), coarse sand (0.75 mm), and very coarse sand (1.5 mm), and (8) changing ground cover conditions such as gravel pavement on the roads, sparse and dense grass or vegetation on the cut or fill slope.

Graphs: The following five major categories of graphs were generated:

(1) Rainfall Excess Determination - Figure 2 gives the ponding time from which surface runoff begins for different soils and rainfall intensities. Figures 3, 4, and 5 provide rainfall excess rates resulting from different rainfall intensities for five selected soils (Muren fine clay, Ida silt loam, Columbia sandy loam, plain field sand, and Poudre fine sand) and for storm durations of 15 min., 30 min., and 60 min. respectively. These graphs can be used to estimate water yields and rainfall excess rates. The infiltration model developed by Li et al. (1976) was used to generate these graphs. The infiltration is formulated to be a function of saturated hydraulic conductivity, average capillary suction pressure, soil porosity, antecedent moisture content, and moisture content in the wetted zone.

(2) Soil Detachment Determination - This soil detachment can result from both raindrop splash and surface runoff erosion. Figure 6 shows a set of assumed raindrop splash detachment rates. The

raindrop splash detachment rate is assumed to be a power function of rainfall intensity (Foster and Meyer, 1975). Table 1 gives the overall runoff detachment coefficients for different particle sizes. These coefficients were determined by comparison of the computed results from the simplified procedure and the road sediment model developed by Simons et al. (1976). The runoff detachment coefficients assumed in the road sediment model are also given in Table 1. The overall runoff detachment coefficients are always larger than the runoff detachment coefficients because the overall runoff detachment coefficient determines the integration of the spatial soil detachment.

Table 1. Soil Detachment Coefficient by Surface Runoff

Particle Size (mm)	Classification	Assumed Detachment Coefficient in the Road Sediment Model	Overall Runoff Detachment Coefficient
0.02	clay and silt	0.01	0.06
0.1	very fine sand	0.1	0.6
0.2	fine sand	0.5	1.0
0.4	medium sand	0.5	1.0
0.75	coarse sand	1.0	1.0
1.5	very coarse sand	1.0	1.0

(3) Overland Sediment Discharge Determination - Figures 7-12 provide the relationship between sediment discharge and water discharge for bare soil roadbed with sediment slopes from 0.01 to 0.05 and for six sediment sizes. Figures 13-18 demonstrate the same relationship for slopes from 0.06 to 0.10. Figures 19-24 give those for slopes from 0.11 to 0.15. Figures 25-42 report the similar relationships

for the case of gravel pavement on the road surface. For cut or fill slopes, selected slope gradients which are reasonable considering soil stability are used. Figures 43-48 show the relationship between sediment discharge and water discharge for bare soil cut or fill with gradients from 1:1 (horizontal to vertical) to 5:1 and for six selected sediment sizes. For evaluating the effectiveness of erosion control by grass or other vegetation, Figures 49-60 are respectively two groups of graphs indicating sediment discharge for the sparse and the dense cover conditions. Note that the blank plot in the graph indicates that there is no sediment discharge for the range of conditions indicated. These graphs were generated utilizing the overland surface sediment model by Simons et al. (1975, 1976). The transport capacity is assumed to be a function of local effective bed shear stress, a combination of Meyer-Peter-Muller bed load equation (1960) and the Einstein suspended load procedure (1950).

(4) Ditch Sediment Discharge Determination - The sediment transport capacities of different sediment size in the ditch flow with V-shape having side slope 5:1 (horizontal to vertical) are given in Figures 61-66. The same equation for computing sediment transport capacity as that used in the overland flow was used to generate the graphs. These graphs can be quickly used to design or check the water and sediment conveyance capacity of a ditch.

(5) Culvert Flow Water and Sediment Determination - For a safe conveyance of water and sediment through a cross drain culvert system, a proper design of culvert flow is very important. Inadequate design of culvert can cause serious problems in the road drainage system and endanger the stability of the roadway. Figure 67 provides the water

conveyance capacities for various design slopes and sizes of culvert. A commercial pipe with Manning's roughness approximately 0.025 is assumed for this procedural guide. Figures 68-73 show sediment transport capacities of different sediment sizes for various design slopes and sizes of culvert. These were determined utilizing the equation by Graf and Acaroglu (1968).

Limitations of the Preliminary Procedural Guide

This preliminary procedural guide has been tested utilizing the road sediment model. The comparison of water yield computations by both methods are excellent and a very good comparison also exists for the sediment yield (see Figs. 74 and 75). However, the road sediment model has not been validated using any field data. Both the current road sediment model and the procedural guide can only be applied qualitatively. That is, this preliminary guide can be used to assess the relative quantities of sediment from road but not to predict the actual amount of sediment produced. In addition, this procedural guide is only valid within the range of data or factors considered.

III. EXAMPLES

In order to demonstrate the utility of the developed procedural guide the following examples are presented.

Example I. Water Yield

Given:

Road surface longitudinal gradient : 3 percent

Length: 500 ft

Width: 10 ft

Soil: fine clay, bare soil surface, sediment size is 0.02 mm and porosity is 0.5 (Muren fine clay)

Design storm: intensity 3 in./hr

duration 30 min

What is the total water yield of the storm?

The procedure follows:

Step 1: From Fig. 2 with rainfall intensity 3 in./hr and Muren fine clay one can estimate the ponding time:

$$T_p = 8 \text{ min}$$

The ponding time is less than the duration of storm, and surface runoff occurs. Then the duration of excess rainfall is

$$T_e = T - T_p = 30 - 8$$
$$= 22 \text{ min}$$

Where T_p is the ponding time from which runoff begins, T_e is the duration of excess rainfall, and T is the duration of storm.

Step 2: From Fig. 4 with rainfall duration of 30 min and Muren fine clay the excess rainfall rate:

$$i_e = 1.25 \text{ in./hr}$$

Where i_e is the excess rainfall rate.

Step 3: The total water yield is

$$\begin{aligned} Y_w &= i_e T_e \\ &= 1.25 \times 22/60 \\ &= 0.46 \text{ in.} \end{aligned}$$

Where Y_w is the water yield in depth of water.

Example II. Sediment Yield from Bare-Soil Road Surface

What would be the sediment yield of the storm using the data given in Example I?

Step 1: Determine the duration of excess rainfall and excess rainfall rate as those in Example I.

Step 2: The maximum discharge per unit width of road is

$$\begin{aligned} q &= i_e L = 1.25 \times 500/43{,}200 \\ &= 0.0144 \text{ ft}^3\text{/sec/ft} \end{aligned}$$

Where q is the discharge per unit width of road, L is the length of road, or cross drain spacing, and 43,200 is a conversion factor from inches per hour to feet per second.

Step 3: With slope $S = 0.03$, $q = 0.0144$ ft^3/sec/ft and sediment size $d_s = 0.02$ mm, Fig. 7 shows that,

$$q_s = 0.88 \text{ lb/sec/ft}$$

Where q_s is the sediment transport rate per unit width of the road and S is the road gradient.

Step 4: The total transport capacity for the entire width of road surface Q_s is,

$$Q_s = q_s \ W = 0.88 \times 10$$
$$= 8.8 \text{ lb/sec}$$

Where W is the width of road surface.

Step 5: The total potential transport capacity for the storm expresses as volume is,

$$\forall_t = Q_s \ T_e/\gamma_s$$
$$= 8.8 \times 22 \times 60/165$$
$$= 70.4 \text{ ft}^3$$

Where γ_s is the specific weight of sediment, it is assumed to be 165 lb/ft^3 in this report.

Step 6: From Fig. 6 the volume of loose soil available from raindrop impact detachment during the storm can be estimated by

$$\forall_r = D_r \ T \ A(1-n)$$
$$= 0.009 \times 30/60 \times 1/12 \times 500 \times 10 \times 0.5$$
$$= 0.94 \text{ ft}^3$$

Where $\forall_r$ is the available loose soil by raindrop splash in volume, D_r is the raindrop-splash soil detachment rate, A is the area, and n is the porosity of soil.

Step 7: Determine the volume of loose soil available from runoff detachment by comparing $\forall_t$ and $\forall_r$.

Because $\forall_r < \forall_t$, the transport capacity is greater than the availability, soil detachment by runoff occurs and its amount is,

$$\forall_f = D_f (\forall_t - \forall_r)$$
$$= 0.06 \times (70.4 - 0.94)$$
$$= 4.17 \text{ ft}^3$$

Where $\forall_f$ is the available loose soil by runoff detachment, D_f is the overall runoff detachment coefficient. For clay and silt, D_f is 0.06 according to Table 1.

Step 8: Determine the total volume of loose soil available for transport during the storm by

$$\forall_a = \forall_r + \forall_f$$
$$= 0.94 + 4.17$$
$$= 5.11 \text{ ft}^3$$

Where $\forall_r$ is the total available loose soil in volume.

Step 9: Determine the amount of soil erosion or sediment yield from road surface by comparing $\forall_t$ and $\forall_a$.

Because $\forall_a < \forall_t$ the availability of loose soil determine the yield. The sediment yield is

$$Y_s = \forall_a = 5.11 \text{ ft}^3$$
$$= 843 \text{ lb}$$

Example III. Sediment Yield from Gravel-Paved Road Surface

Estimate the sediment yield if the surface is paved with gravel. Assume ground cover density is 0.9.

Step 1: Determine the duration of excess rainfall, excess rainfall rate, maximum discharge rate as those in Example II.

Step 2: With the slope $S = 0.03$, $q = 0.0144 \text{ ft}^3/\text{sec/ft}$ and sediment size d_s = 0.02 mm, Fig. 25 shows that,

$$q_s = 0.18 \text{ lb/ft/sec}$$

Step 3: The total transport capacity for the entire width of road surface is

$$Q_s = q_s W = 0.18 \times 10$$
$$= 1.8 \text{ lb/sec}$$

Step 4: The total potential transport capacity for the storm expressed as volume is,

$$\forall_s = Q_s T_e/\gamma_s$$
$$= 1.8 \times 22 \times 60/165$$
$$= 14.4 \text{ ft}^3$$

Step 5: Because the gravel pavement can effectively protect the soil surface from raindrop splash detachment, The loose soil available from raindrop splash should be modified as follows (see Example II).

$$\forall_r = DTA(1-n)(1-D_g)$$
$$= 0.009 \times 30/60 \times 1/12 \times 500 \times 10 \times 0.5 \times (1-0.9)$$
$$= 0.094 \text{ ft}^3$$

Where D_g is the ground cover density.

Step 6: Determine the volume of loose soil available from runoff detachment by comparing $\forall_t$ and $\forall_r$.

Because $\forall_r < \forall_t$, soil detachment by runoff occurs and its amount is,

$$\forall_f = D_f (\forall_t - \forall_r)$$
$$= 0.06 \times (14.4 - 0.094)$$
$$= 0.86 \text{ ft}^3$$

Step 7: Determine the total volume of loose soil available for transport during the storm by

$$\forall_a = \forall_r + \forall_f$$
$$= 0.094 + 0.86$$
$$= 0.95 \text{ ft}^3$$

Step 8: Determine the amount of soil erosion by comparing $\forall_t$ and $\forall_a$.

Because $\forall_a < \forall_t$, the availability of loose soil determines the yield. The amount of sediment yield is

$$Y_s = \forall_a = 0.95 \text{ ft}^3$$
$$= 157 \text{ lb}$$

The sediment yield with gravel pavement on the surface would be only 19 percent of that from bare surface.

Example IV. Sediment Yield and Spacing of Cross Drain

For Example I what would be the erosion rate if the spacing of cross drain is modified to be only 100 ft?

Step 1: The maximum discharge per unit width of road is,

$$q = i_e L = 1.25 \times 100/43{,}200$$
$$= 0.0029 \text{ ft}^3\text{/sec/ft}$$

Step 2: With the slope $S = 0.03$, $q = 0.0029 \text{ ft}^3\text{/sec/ft}$ and sediment size $d_s = 0.02$ mm, Fig. 7 provides that

$$q_s = 0.10 \text{ lb/sec/ft}$$

Step 3: The total transport capacity for the entire width of road surface is

$$Q_s = q_s W = 0.10 \times 10$$
$$= 1.0 \text{ lb/sec}$$

Step 4: The total petential transport capacity for the storm is,

$$\mathcal{V}_t = Q_s \, T_e / \gamma_s$$
$$= 1.0 \times 22 \times 60/105$$
$$= 8.0 \text{ ft}^3$$

Step 5: The available loose soil from raindrop impact is

$$\mathcal{V}_r = D_r \, TA(1-n)$$
$$= 0.009 \times 30/60 \times 1/12 \times 100 \times 10 \times 0.5$$
$$= 0.19 \text{ ft}^3$$

Step 6: The amount of loose soil detached by surface runoff is

$$\mathcal{V}_f = D_f \, (\mathcal{V}_t - \mathcal{V}_r)$$
$$= 0.06 \times (8.0 - 0.19)$$
$$= 0.47 \text{ ft}^3$$

Step 7: The total volume of loose soil available for transport during the storm is,

$$\mathcal{V}_a = \mathcal{V}_r + \mathcal{V}_f$$
$$= 0.19 + 0.47$$
$$= 0.66 \text{ ft}^3$$

Step 8: The total sediment yield can be determined by comparing $\mathcal{V}_t$ and $\mathcal{V}_a$.

Because $\mathcal{V}_r < \mathcal{V}_a$, the availability of loose soil determines the yield. The sediment yield is

$$Y_s = \mathcal{V}_a = 0.66 \text{ ft}^3$$
$$= 109 \text{ lb}$$

The total yield considering 500 ft road for this alternative design would be,

$$Ys = 5 \times 109$$
$$= 545 \text{ lb}$$

This value is less than those computed in Example II. This reduction of sediment production by shortening the flow concentration path is not too significant but the reduction of water flow concentration may greatly reduce the erosive potential of runoff from collective ditches on or below the road fill. However, the decision of spacing for cross drain should consider economic trade-off in order to have an optimum design.

<u>Example V. Sediment Yield for a Larger Sediment Size</u>

Given:

Road surface longitudinal gradient: 10 percent

Length: 200 ft

Width: 10 ft

Soil: Medium sand, bare soil surface, sediment size is 0.4 mm and porosity is 0.5 (plain field sand)

Design storm: intensity 10 in./hr

duration 30 min

What is the sediment yield of the storm?

<u>Step 1</u>: From Fig. 2 with rainfall intensity 10 in./hr and plain field sand one can estimate the time of ponding:

$$T_p = 6 \text{ min}$$

The duration of excess rainfall is,

$$T_e = T - T_p = 30 - 6$$
$$= 24 \text{ min}$$

Step 2: From Fig. 4 with rainfall duration of 30 min rainfall intensity of 10 in./hr and plain field sand the excess rainfall rate is,

$$i_e = 2.7 \text{ in./hr}$$

Step 3: The maximum discharge per unit width of road is

$$q - i_e L = 2.7 \times 200/43{,}200$$
$$= 0.0125 \text{ ft}^3\text{/sec/ft}$$

Step 4: With slope $S = 0.1$, $q = 0.0125$ ft^3/sec/ft and $d_s = 0.4$ mm, Fig. 16 gives that,

$$q_s = 0.028 \text{ lb/sec/ft}$$

Step 5: The total transport capacity is

$$Q_s = q_s W = 0.028 \times 10$$
$$= 0.28 \text{ lb/sec}$$

Step 6: The total potential transport capacity for the storm expressed in volume is,

$$\mathcal{V}_t = Q_s\, T_e/\gamma_s$$
$$= 0.28 \times 24 \times 60/165$$
$$= 2.44 \text{ ft}^3$$

Step 7: From Fig. 6 the volume of loose soil available from raindrop impact is:

$$\mathcal{V}_r = D_r\, TA(1-n)$$
$$= 0.1 \times 30/60 \times 1/12 \times 200 \times 10 \times 0.5$$
$$= 4.17 \text{ ft}^3$$

Step 8: Because $\mathcal{V}_t < \mathcal{V}_r$, transport capacity governs the sediment yield. The sediment yield is then,

$$Y_s = \mathcal{V}_t$$
$$= 2.44 \text{ ft}^3$$
$$= 403 \text{ lb}$$

Example VI. Sediment Yield from Bare-Soil Fill Slope

Given:

Fill slope gradient: 2:1 (horizontal to vertical)

Vertical distance 50 ft

Width: 10 ft

Soil: fine clay, bare soil surface, sediment size is 0.02 mm and porosity is 0.5 (Muren fine clay)

Design Storm: intensity 3 in./hr
duration 30 min

What is the sediment yield of the storm?

Step 1: The duration of excess rainfall and excess rainfall rate are the same as Example I, i.e.,

$$T_e = 22 \text{ min}$$

and

$$i_e = 1.25 \text{ in./hr}$$

Step 2: The horizontal length is

$$L = 2 \times 50$$
$$= 100 \text{ ft}$$

Step 3: The maximum discharge per unit width of road is

$$q = i_eL = 1.25 \times 100/43{,}200$$
$$= 0.0029 \text{ ft}^3\text{/sec/ft}$$

Step 4: With the slope 2:1, $q = 0.0029$ ft^3/sec/ft, $d_s = 0.02$ mm and bare soil, Fig. 43 shows that

$$q_s = 0.81 \text{ lb/sec ft}$$

Step 5: Total transport capacity is

$$Q_s = q_sW = 0.81 \times 10$$
$$= 8.1 \text{ lb/sec}$$

Step 6: The total transport capacity in volume is,

$$\forall_t = Q_s T_e / \gamma_s$$
$$= 8.1 \times 22 \times 60/165$$
$$= 64.8 \text{ ft}^3$$

Step 7: The volume of soil detached by raindrop splash is

$$\forall_r = D_r \, TA(1-n)$$
$$= 0.009 \times 30/60 \times 1/12 \times 100 \times 10 \times 0.5$$
$$= 0.19 \text{ ft}^3$$

Step 8: Because $\forall_r < \forall_t$, from Fig. 7 the volume of loose soil available from runoff detachment can be determined as follows,

$$\forall_f = D_f \, (\forall_t - \forall_r)$$
$$= 0.06 \times (64.8 - 0.19)$$
$$= 3.88 \text{ ft}^3$$

Step 9: The total amount of loose soil available for transport

$$\forall_a = \forall_r + \forall_f$$
$$= 0.19 + 3.88$$
$$= 4.07 \text{ ft}^3$$

Step 10: Determine the amount of sediment yield by comparing $\forall_t$ and $\forall_a$.

Because $\forall_a < \forall_t$, the availability controls the sediment yield, i.e.,

$$Y_s = \forall_a = 4.07 \text{ ft}^3$$
$$= 672 \text{ lb}$$

Example VII. Sediment Yield from Sparse-Vegetation Fill Slope

What is the sediment yield if the slope in Example VII is protected by sparse vegetation and grass?

Assume that the ground cover density is 0.3.

Step 1: With the slope 2:1, $q = 0.0029$ ft^3/sec/ft, $d_s = 0.02$ mm and sparse grass one can determine the transport capacity using Fig. 49 as follows.

$$q_s = 0.012 \text{ lb/sec/ft}$$

Step 2: The total transport capacity in volume is

$$\begin{aligned} \forall_t &= q_s\, W\, T_e/\gamma_s \\ &= 0.012 \times 10 \times 22 \times 60/165 \\ &= 0.96 \text{ ft}^3 \end{aligned}$$

Step 3: The volume of loose soil available from raindrop impact is

$$\begin{aligned} \forall_r &= D_r\, TA(1-n)(1-D_g) \\ &= 0.19 \times (1-0.3) \\ &= 0.13 \text{ ft}^3 \end{aligned}$$

Step 4: The volume of loose soil supplied from runoff erosion is

$$\begin{aligned} \forall_f &= D_f\, (\forall_t - \forall_r) \\ &= 0.06 \times (0.96 - 0.13) \\ &= 0.049 \text{ ft}^3 \end{aligned}$$

Step 5: The total loose soil available for transport is

$$\begin{aligned} \forall_a &= \forall_r + \forall_f \\ &= 0.179 \text{ ft}^3 \end{aligned}$$

Step 6: Because $\forall_a < \forall_t$, the sediment yield is,

$$\begin{aligned} Y_s = \forall_a &= 0.179 \text{ ft}^3 \\ &= 29.6 \text{ lb} \end{aligned}$$

This value is only 4.4 percent of that determined in Example VI.

Example VIII. Sediment Yield from Dense-Vegetation Fill Slope

What is the sediment yield if the slope in Example VI is protected by dense grass?

Assume that the ground cover density is 0.9.

Step 1: Following a similar procedure as Example VII it is not difficult to determine that (from Fig. 55 with $q = 0.0029\ ft^3/sec/ft$, $d_s = 0.02$ mm, and slope 2:1)

$$q_s = 0.0005 \text{ lb/sec/ft}$$

Step 2: The total transport capacity in volume is,

$$\begin{aligned} V_t &= q_s\, W\, T_e/\gamma_s \\ &= 0.0005 \times 10 \times 22 \times 60/165 \\ &= 0.04\ ft^3 \end{aligned}$$

Step 3: The volume of loose soil from raindrop impact is,

$$\begin{aligned} V_r &= D_r\, TA(1-n)(1-D_g) \\ &= 0.019\ ft^3 \end{aligned}$$

Step 4: The volume of loose soil from surface runoff is

$$\begin{aligned} V_f &= D_f\, (V_t - V_r) \\ &= 0.06 \times (0.04 - 0.019) \\ &= 0.0013\ ft^3 \end{aligned}$$

Step 5: The total loose soil available for transport is,

$$\begin{aligned} V_a &= V_r + V_f \\ &= 0.019 + 0.0013 \\ &= 0.0203\ ft^3 \end{aligned}$$

Step 6: The sediment is governed by the availability, i.e.,

$$\begin{aligned} Y_s &= V_a = 0.0203\ ft^3 \\ &= 3.35 \text{ lb} \end{aligned}$$

This value is only 0.5 percent of that computed in Example VI.

Example IX. Sediment Yield Considering Different Sizes

Given:

Road surface longitudinal gradient: 3 percent

Length: 500 ft

Width: 10 ft

Soil: A mixture of fine clay, very fine sand, and fine sand, bare soil surface, and porosity is 0.5 (Muren fine clay).

Size Distribution: 0.02 mm - 50%

0.1 - 30%

0.2 mm - 20%

Design Storm: intensity 3 in./hr

duration 30 min

What is the sediment yield of the storm

Step 1: Determine the duration of excess rainfall, the rainfall excess rate, and the maximum discharge following the same procedures as those in Example I.

Step 2: Determine the sediment transport capacities for different sizes with $q = 0.0144\ ft^3/sec/ft$ from Figs. 7, 8, and 9. The results are:

$$q_{s1} = 0.88\ lb/sec/ft$$

$$q_{s2} = 0.038\ lb/sec/ft$$

$$q_{s3} = 0.011\ lb/sec/ft$$

where q_{si} is the transport rate for the ith size.

<u>Step 3</u>: The total potential transport capacities for the storm are:

$$\forall_{t1} = P_1 \, q_{s1} \, W \, T_e/\gamma_s$$
$$= 0.5 \times 0.88 \times 10 \times 22 \times 60/165$$
$$= 35.2 \text{ ft}^3$$

$$\forall_{t2} = P_2 \, q_{s2} \, W \, T_e/\gamma_s$$
$$= 0.3 \times 0.038 \times 10 \times 22 \times 60/165$$
$$= 0.91 \text{ ft}^3$$

$$\forall_{t3} = P_3 \, q_{s3} \, W \, T_e/\gamma_s$$
$$= 0.2 \times 0.011 \times 10 \times 22 \times 60/165$$
$$= 0.18 \text{ ft}^3$$

$$\forall_t = \forall_{t1} + \forall_{t2} + \forall_{t3} = 36.29$$

when P_i is the fraction for the ith size.

<u>Step</u> 4: The volumes of loose soil available from raindrop impact for different sizes are:

$$\forall_r = D_r \, TA(1-n) = 0.009 \times 30/60 \times 1/12 \times 500 \times 10 \times 0.5$$
$$= 0.94 \text{ ft}^3$$

$$\forall_{r1} = P_1 \, \forall_r$$
$$= 0.5 \times 0.94$$
$$= 0.47 \text{ ft}^3$$

$$\forall_{r2} = P_2 \, \forall_r$$
$$= 0.3 \times 0.94$$
$$= 0.28 \text{ ft}^3$$

$$\forall_{r3} = P_3 \, \forall_r$$
$$= 0.2 \times 0.94$$
$$= 0.19 \text{ ft}^3$$

Step 5: The volumes of loose soil available from runoff detachment are:

$$\forall_f = D_f(\forall_t - \forall_r)$$
$$= 0.06 \times (36.29 - 0.94)$$
$$= 2.12$$

$$\forall_{f1} = P_1 \forall_f$$
$$= 0.5 \times 2.12$$
$$= 1.06 \text{ ft}^3$$

$$\forall_{f2} = P_2 \forall_f$$
$$= 0.3 \times 2.12$$
$$= 0.64 \text{ ft}^3$$

$$\forall_{f3} = P_3 \forall_f$$
$$= 0.2 \times 2.12$$
$$= 0.42 \text{ ft}^3$$

where D_f is assumed to be 0.06 for the sediment mixture.

Step 6: The total volumes of loose soil available for transport are:

$$\forall_{a1} = \forall_{r1} + \forall_{f1}$$
$$= 0.47 + 1.06$$
$$= 1.53 \text{ ft}^3$$

$$\forall_{a2} = \forall_{r2} + \forall_{f2}$$
$$= 0.28 + 0.64$$
$$= 0.92 \text{ ft}^3$$

$$\forall_{a3} = \forall_{r3} + \forall_{f3}$$
$$= 0.19 + 0.42$$
$$= 0.61 \text{ ft}^3$$

Step 7: The sediment yields for each size are:

$$Y_{s1} = \forall_{a1} = 1.53 \text{ ft}^3$$
$$= 252 \text{ lb}$$

$$Y_{s2} = \forall_{a2} = 0.91 \text{ ft}^3$$
$$= 150 \text{ lb}$$

and

$$Y_{s3} = \forall_{t3} = 0.18\ ft^3$$
$$= 30\ lb$$

Total sediment yield is then

$$Y_s = Y_{s1} + Y_{s2} + Y_{s3}$$
$$= 432\ lb$$

Example X. Annual Sediment Yield

Given:

Road surface longitudinal gradient: 3 percent

Length: 100 ft

Width: 10 ft

Soil: fine clay, bare soil surface, sediment size is 0.02 mm, and porosity is 0.5 (Muren fine clay)

Design storms for a typical year:

Storm No. 1: intensity 3 in./hr
duration 60 min

Storm No. 2: intensity 5 in. /hr
duration 30 min

Storm No. 3: intensity 10 in./hr
duration 15 min

What is the annual sediment yield if the expected numbers of occurrence of storms in a year are as follows?

Storm	Numbers of Occurrence
No.1	5
No. 2	3
No. 3	2

Step 1: From Fig. 2 the ponding times are:

$$T_{p1} = 8 \text{ min for } 3 \text{ in./hr}$$

$$T_{p2} = 3 \text{ min for } 5 \text{ in./hr}$$

$$T_{p3} = 0.7 \text{ min for } 10 \text{ in./hr}$$

Where the subscript indicate the storm number.

Step 2: The rainfall excess rates can be determined by Figs. 3, 4 and 5 as follows.

$$i_{e1} = 1.6 \text{ in./hr for } 3 \text{ in./hr and } 60 \text{ min duration}$$

$$i_{e2} = 3.2 \text{ in./hr for } 5 \text{ in./hr and } 30 \text{ min duration}$$

$$i_{e3} = 7.3 \text{ in./hr for } 10 \text{ in./hr and } 15 \text{ min duration}$$

Step 3: The maximum water discharges are:

$$q_1 = i_{e1}L = 0.00370 \text{ ft}^3/\text{sec/ft}$$

$$q_2 = i_{e2}L = 0.00741 \text{ ft}^3/\text{sec/ft}$$

$$q_3 = i_{e3}L = 0.01690 \text{ ft}^3/\text{sec/ft}$$

Step 4: From Fig. 7 one can determine the total transport capacities for each storm in volume as follows.

$$\begin{aligned} \forall_{t1} &= q_{s1}\, W(T_1 - T_{p1})/\gamma_s \\ &= 0.15 \times 10 \times (60 - 8) \times 60/165 \\ &= 28.36 \text{ ft}^3 \end{aligned}$$

$$\begin{aligned} \forall_{t2} &= q_{s2}\, W(T_1 - T_{p2})/\gamma_s \\ &= 0.35 \times 10 \times (30 - 3) \times 60/165 \\ &= 34.36 \text{ ft}^3 \end{aligned}$$

$$\begin{aligned} \forall_{t3} &= q_{s3}\, W(T_1 - T_{p3})/\gamma_s \\ &= 0.91 \times 10 \times (15 - 0.7) \times 60/165 \\ &= 47.32 \text{ ft}^3 \end{aligned}$$

Step 5: The volumes of loose soil available from raindrop splash for each storm are

$$V_{r1} = D_{r1}\, T_1\, A(1-n)$$
$$= 0.009 \times 60/60 \times 1/12 \times 100 \times 10 \times 0.5$$
$$= 0.38 \text{ ft}^3$$

$$V_{r2} = D_{r2}\, T_2\, A(1-n)$$
$$= 0.025 \times 30/60 \times 1/12 \times 100 \times 10 \times 0.5$$
$$= 0.52 \text{ ft}^3$$

$$V_{r3} = D_{r3}\, T_3\, A(1-n)$$
$$= 0.1 \times 15/60 \times 1/12 \times 100 \times 10 \times 0.5$$
$$= 1.04 \text{ ft}^3$$

Step 6: The volumes of loose soil available from runoff detachment are:

$$V_{f1} = D_f(V_{t1} - V_{r1})$$
$$= 0.06 \times (28.36 - 0.38)$$
$$= 1.67 \text{ ft}^3$$

$$V_{f2} = D_f(V_{t2} - V_{r2})$$
$$= 0.06 \times (34.36 - 0.52)$$
$$= 2.03 \text{ ft}^3$$

$$V_{f3} = D_f(V_{t3} - V_{r3})$$
$$= 0.06 \times (47.32 - 1.04)$$
$$= 2.75 \text{ ft}^3$$

Step 7: The total values of loose soil available for transport for each storm are:

$$V_{a1} = 2.05 \text{ ft}^3$$
$$V_{a2} = 2.55 \text{ ft}^3$$
$$V_{a3} = 3.82 \text{ ft}^3$$

Step 8: The sediment yields of each storm are:

$$Y_{s1} = V_{a1} = 2.05 \text{ ft}^3 = 338 \text{ lb}$$
$$Y_{s2} = V_{a2} = 2.55 \text{ ft}^3 = 421 \text{ lb}$$
$$Y_{s3} = V_{a3} = 3.82 \text{ ft}^3 = 630 \text{ lb}$$

Step 9: Assuming the ground cover condition soil particle distribution, and erodibility are the same for the whole year, the annual sediment yield is then

$$Y_a = N_1 Y_{s1} + N_2 Y_{s2} + N_3 + Y_{s3}$$
$$= 5 \times 338 + 3 \times 421 + 2 \times 630$$
$$= 4{,}213 \text{ lb}$$

Example XI. Sediment Yield from Alternative Routes

Given the following two alternative routes

Route A:

Road surface longitudinal gradient: 10 percent

Length: 1,000 ft with one cross drain

Width: 10 ft

Soil: fine clay, base soil surface, dominant sediment size 0.02 mm and porosity is 0.5 (Muren fine clay)

Route B:

Road surface longitudinal gradient: 5 percent

Length: 2,000 ft with three cross drains

Width: 10 ft

Soil: very fine sand, base soil surface, dominant size 0.1 mm and porosity is 0.5 (Columbia Sandy Loam)

Which alternative route would produce a smaller amount of sediment from road surface for the design storm of intensity 7 in./hr and duration 30 min?

Step 1: Determine lengths of microdrainage for the two routes by considering total length and numbers of cross drain. The length is 500 ft for both routes. Route A has two and Route B has four microdrainage systems respectively.

Step 2: From Fig. 2 the ponding times are:

T_{p1} = 1.6 min for Route A (Muren fine clay)

T_{p2} = 9 min for Route B (Columbia Sandy Loam)

Then, the effective rainfall durations are

$$T_{e1} = 28.4 \text{ min}$$

$$T_{e2} = 21.0 \text{ min}$$

Step 3: The rainfall excess rates can be determined by Fig. 4 as follows:

$$i_{e1} = 5 \text{ in./hr}$$

$$i_{e2} = 2.2 \text{ in./hr}$$

Then i the maximum discharge for each microdrainage is respectively,

$$q_1 = 0.0579 \text{ ft}^3\text{/sec/ft}$$

$$q_2 = 0.0255 \text{ ft}^3\text{/sec/ft}$$

Step 4: From Figs. 8 and 13 one can determine the sediment transport capacities for each microdrainage as follows:

$$q_{s1} = 16 \text{ lb/sec/ft} \quad \text{(Fig. 13)}$$

$$q_{s2} = 0.17 \text{ lb/sec/ft} \quad \text{(Fig. 8)}$$

Step 5: The total transport capacity of the storm in volume for each microdrainage is:

$$\begin{aligned} \mathcal{V}_{t1} &= q_{s1}\, W\, T_{e1}/\gamma_s \\ &= 16 \times 10 \times 28.4 \times 60/165 \\ &= 1652.4 \text{ ft}^3 \end{aligned}$$

$$\begin{aligned} \mathcal{V}_{t2} &= q_{s2}\, W\, T_{e2}/\gamma_s \\ &= 0.17 \times 10 \times 21 \times 60/165 \\ &= 13.0 \text{ ft}^3 \end{aligned}$$

Step 6: The volume of loose soil available from raindrop splash for each microdrainage is:

$$\begin{aligned} \mathcal{V}_{r1} &= D_{r1}\, T_1\, A(1-n) \\ &= 0.049 \times 30/60 \times 1/12 \times 500 \times 10 \times 0.5 \\ &= 5.1 \text{ ft}^3 \end{aligned}$$

$$\begin{aligned} \mathcal{V}_{r2} &= \mathcal{V}_{r1} \\ &= 5.1 \text{ ft}^3 \end{aligned}$$

Step 7: The volume of loose soil available from runoff detachment for each microdrainage is:

$$\begin{aligned} \mathcal{V}_{f1} &= D_{f1}(\mathcal{V}_{t1} - \mathcal{V}_{r1}) \\ &= 0.06 \times (1652.4 - 5.1) \\ &= 98.84 \text{ ft}^3 \end{aligned}$$

$$\forall_{f2} = D_{f2}(\forall_{t2} - \forall_{r2})$$
$$= 0.6 \times (13.0 - 5.1)$$
$$= 4.74 \text{ ft}^3$$

Step 8: The total loose soil available for transport is

$$\forall_{a1} = 103.94 \text{ ft}^3$$
$$\forall_{a2} = 9.84 \text{ ft}^3$$

Step 9: Soil erosion from each microdrainage is as follows:

$$E_1 = \forall_{a1} = 103.94 \text{ ft}^3$$
$$= 17{,}150 \text{ lb}$$
$$E_2 = \forall_{a2} = 9.84 \text{ ft}^3$$
$$= 1{,}624 \text{ lb}$$

Step 10: The total sediment yields from two different alternative routes are:

$$Y_{s1} = 2 \times 17{,}150$$
$$= 34{,}300 \text{ lb (Route A)}$$
$$Y_{s2} = 4 \times 1624$$
$$= 6{,}496 \text{ lb (Route B)}$$

Thus although Route A is shorter it will contribute much more sediment from road surface than Route B. Of course the decision on the alternative route location is dependent on many other factors such as cut and fill slopes, interaction with watershed, social and legal constraints, economic trade-off, and maintenance problems etc.

Example XII. Sediment Yield from Alternative Cross Section Designs

Given the following two alternative cross section designs

Design A: In-slope design

Road transverse gradient: 3 percent

Length: 50 ft (longitudinal)

Width: 15 ft

Fill slope gradient: 2:1 (horizontal to vertical)

Vertical distance: 15 ft

Soil: fine clay, base soil surface, sediment size is 0.02 mm and porosity is 0.5 (Muren fine clay)

Design B: Same soil type and design dimension as Design A except that this design is an out-slope cross section.

Which design alternative will produce a smaller sediment from road surface and fill slope for the design storm of intensity 10.0 in./hr and duration 30 min?

Step 1: Determine the duration of excess rainfall and excess rainfall rate following a similar procedure as in Example I, i.e.,

$$T_e = 29.3 \text{ min}$$

$$i_e = 8.0 \text{ in./hr}$$

Step 2: The maximum discharge per unit width of road is

$$q = i_e L = 18.0 \times 15$$
$$= 0.00278 \text{ ft}^3\text{/sec/ft}$$

Step 3: From Fig. 7 the total transport capacity of the road surface is

$$\Psi_t = q_s \, W \, T_e/\gamma_s$$
$$= 0.09 \times 50 \times 29.3 \times 60/165$$
$$= 47.95 \text{ ft}^3$$

Step 4: From Fig. 6, the loose soil available from raindrop splash on road surface is

$$\Psi_r = D_r \, T \, A(1-n)$$
$$= 0.1 \times 30/60 \times 1/12 \times 15 \times 50 \times 0.5$$
$$= 1.56 \text{ ft}^3$$

Step 5: The loose soil available from runoff detachment on road surface is

$$\forall_f = D_f(\forall_t - \forall_r)$$
$$= 0.05 \times (47.95 - 1.56)$$
$$= 2.78 \text{ ft}^3$$

Step 6: The total loose soil available on road surface is

$$\forall_a = 4.34 \text{ ft}^3$$

Step 7: The sediment yield from road surface

$$Y_s = \forall_a = 4.34 \text{ ft}^3$$
$$= 716 \text{ lb}$$

Step 8: For Design A (in-slope) the fill slope is conceptually an independent response unit. Its sediment yield can be determined following the similar procedures as outlined in Example VI, i.e.,

$$L = 2 \times 15 = 30$$
$$q = i_e L = 8 \times 30/63{,}200$$
$$= 0.00556$$
$$q_s = 1.8 \text{ lb/sec/ft (from Fig. 43)}$$
$$Q_s = q_s W = 1.8 \times 50$$
$$= 90 \text{ lb/sec}$$
$$\forall_t = Q_s T_e / \gamma_s$$
$$= 959 \text{ ft}^3$$
$$\forall_r = D_r T A(1-n)$$
$$= 0.1 \times 30/60 \times 1/12 \times 30 \times 50 \times 0.5$$
$$= 3.13 \text{ ft}^3$$

$$V_f = D_f(V_t - V_r)$$
$$= 0.06 \times (959 - 3.13)$$
$$= 57.35 \text{ ft}^3$$
$$V_a = 60.48 \text{ ft}^3$$
$$Y_s = V_a = 60.48 \text{ ft}^3$$
$$= 9{,}980 \text{ lb}$$

So total sediment yield from road surface and fill slope for Design A is

$$Y_t = 716 + 9{,}980$$
$$= 10{,}696 \text{ lb}$$

Step 9: For Design B (out-slope) the runoff routes from the road surface to the fill slope. The maximum discharge and sediment transport capacity per unit of fill slope should be modified as follows.

$$L = 30 + 15 = 45$$
$$q = i_e L = 8 \times 45/63{,}200$$
$$= 0.00833 \text{ ft}^3/\text{sec/ft}$$
$$q_s = 3.0 \text{ lb/sec/ft (from Fig. 43)}$$
$$Q_s = q_s W = 3.0 \times 50$$
$$= 150 \text{ lb/sec}$$
$$V_t = Q_s T_e/\gamma_s$$
$$= 1{,}598 \text{ ft}^3$$

Step 10: For Design B, the sources of loose soil available for the fill slope are threefold: (1) delivered from road surface, (2) detached from raindrop splash, and (3) detached from surface runoff. The availability from the first two sources is

$$V_r = 4.34 + 3.13$$
$$= 7.47 \text{ ft}^3$$

Then, the volume of loose soil available from surface runoff detachment is

$$\forall_f = D_f(\forall_t - \forall_r)$$
$$= 0.06 \times (1598 - 7.47)$$
$$= 95.43 \text{ ft}^3$$

The total loose soil available is

$$\forall_a = 102.9 \text{ ft}^3$$

The total sediment yield resulting from Design B is

$$Y_s = 102.9 \text{ ft}^3$$
$$= 16{,}979 \text{ lb} > 10{,}696 \text{ lb}$$

This shows that Design A will produce a smaller amount of sediment. In other words, the design of in-slope cross section would generally produce a smaller amount of sediment from road surface and fill slope. However, it is usually necessary to have a ditch and culvert system when a in-slope cross section is designed. This would probably increase construction costs substantially. Therefore, the decision on the alternative design of cross sections should be made considering both engineering and economic aspects.

Example XIII. Ditch Design

Given:

Water discharge per unit length of ditch: $q = 0.002 \text{ ft}^3\text{/sec/ft}$

Sediment discharge per unit length of ditch: $q_s = 0.01 \text{ lb/sec/ft}$

Sediment size: 0.1 mm

Side slope: 5:1 (horizontal to vertical)

Length of ditch: 100 ft

What is the maximum slope for conveying water and sediment without causing additional erosion in the ditch?

Step 1: The maximum water discharge is

$$Q = qL$$
$$= 0.002 \times 100$$
$$= 0.2 \text{ ft}^3/\text{sec}$$

Step 2: The maximum sediment discharge is

$$Q_s = q_s L$$
$$= 0.01 \times 100$$
$$= 1.0 \text{ lb/sec}$$

Step 3: From Fig. 62 with $Q = 0.2$ ft^3/sec and $Q_s = 1.0$ lb/sec one obtains

$$S = 0.04$$

The maximum slope is approximately 4 percent.

Example XIV. Culvert Design

Given:

Water discharge: $Q = 20$ ft^3/sec

Sediment discharge: $Q_s = 20$ lb/sec

Pipe size: $D = 30$ in.

Sediment size: $d_s = 0.2$ mm

What is the minimum slope for conveying both water and sediment without causing sediment deposition in the inlet and culvert?

Step 1: From Fig. 67, $Q = 20$ ft^3/sec, $D = 30$ inches

$$S \geq 0.0022$$

Step 2: From Fig. 70, $Q = 20$ lb/sec, $D = 30$ in.

$$S \geq 0.003$$

Step 3: With the comparison of the above inequalities, one concludes the design slope of culvert should be greater than 0.3 percent if 30 in. circular culvert is used. The protection of culvert outfall should be provided to prevent heat cutting due to high erosive power of water jet at culvert outfall.

Tabular Form

For Example I through Example XII, it is convenient to summarize necessary steps for determining water and sediment yields in a tabular form. Utilizing Examples I and II, Table 2 demonstrates a determination of water sediment yields using such a tabular form.

Table 2. Determination of Water and Sediment Yields

i in./hr (1)	T min (2)	T_p min (3)	T_e min (4)	i_e in./hr (5)	Y_w in. (6)	L ft (7)	q ft^3/sec/ft (8)	S (9)	q_s lb/sec/ft (10)	$\mathcal{V}_t$ ft^3 (11)	$\mathcal{V}_r$ ft^3 (12)	$\mathcal{V}_f$ ft^3 (13)	$\mathcal{V}_a$ ft^3 (14)	Y_s lb (15)
3	30	8	22	1.25	0.46	500	0.0144	0.03	0.88	70.4	0.34	4.7	5.11	843

IV. SUMMARY

This report describes the development, limitations, and examples of applications of a preliminary procedural guide for estimating water and sediment yields from roads in forests. This procedural guide is developed in the form of a series of design graphs. These graphs were generated utilizing the road sediment model developed by Simons et al. (1976) in accordance with some assumptions required for simplification. The graphs relate such variables as rainfall intensity, storm duration, infiltration rate, soil detachment rate, sediment size, ground cover conditions, road gradient, cut and fill slope, sediment discharge and water discharge. These generated graphs can be used by the forest planner or engineer to quickly estimate water and sediment yield from roadways of different designs.

This preliminary procedural guide has been tested utilizing the road sediment model. The comparison of water yield computations by both methods are excellent and the reasonable comparison also exists for the sediment yield. However, the road sediment model has not been validated using field data. Both the current road sediment model and the procedural guide can only be applied qualitatively. That is, this preliminary guide can be used to assess the relative quantities of sediment from road but not to predict the actual amount of sediment produced. In addition, this procedural guide is only valid within the range of data or factors considered.

This procedure guide was developed through constant exchange of ideas and consultation with the personnel from National Forest Service Regions 5, 6, and 8. For their assistance, the writers are greatly indebted.

FIGURES

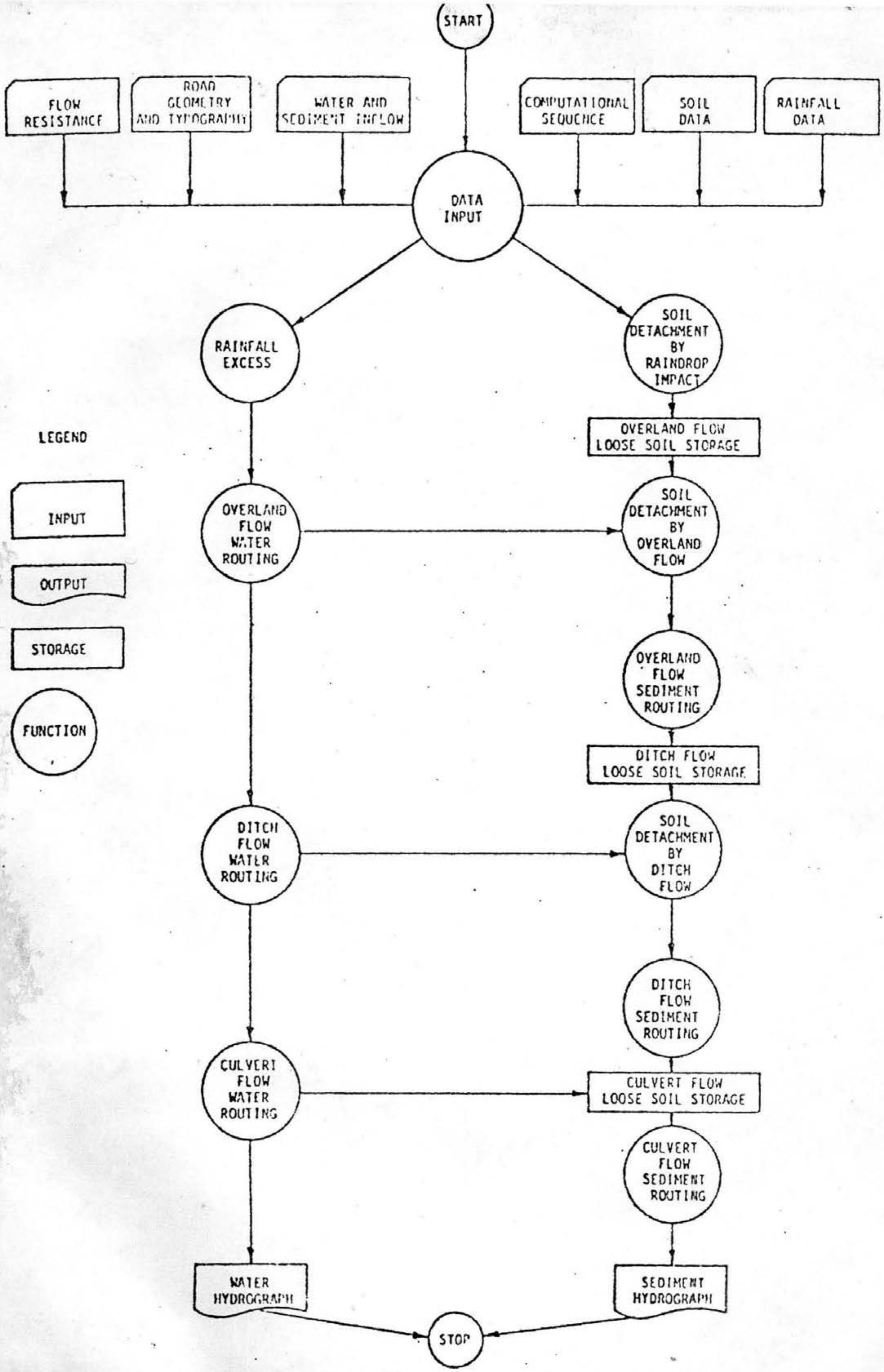

Fig. 1. Schematic Structure of Road Erosion Model

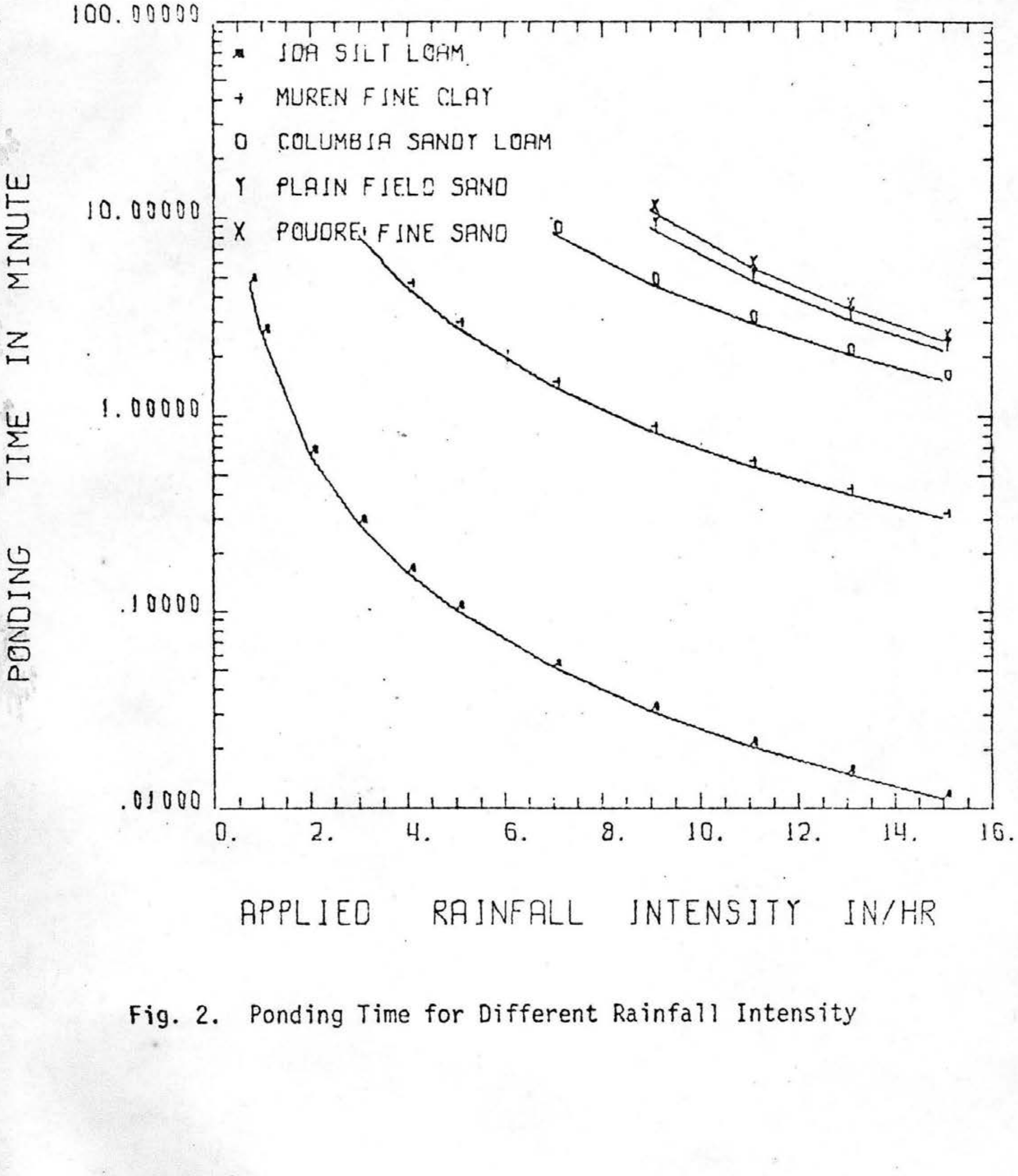

Fig. 2. Ponding Time for Different Rainfall Intensity

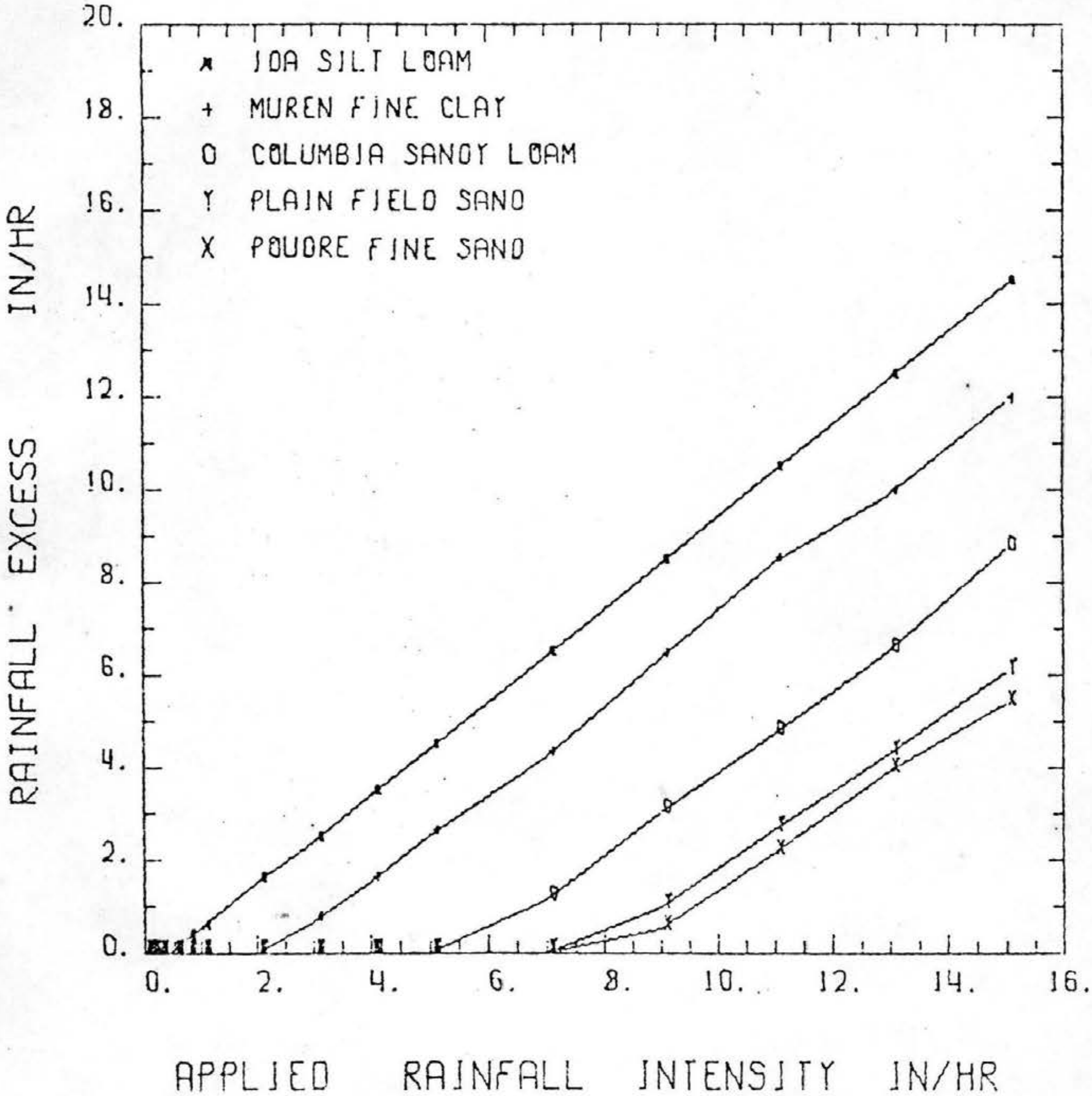

Fig. 3. Rainfall Excess Rate versus Rainfall Intensity for Storm Duration of 15 Minutes

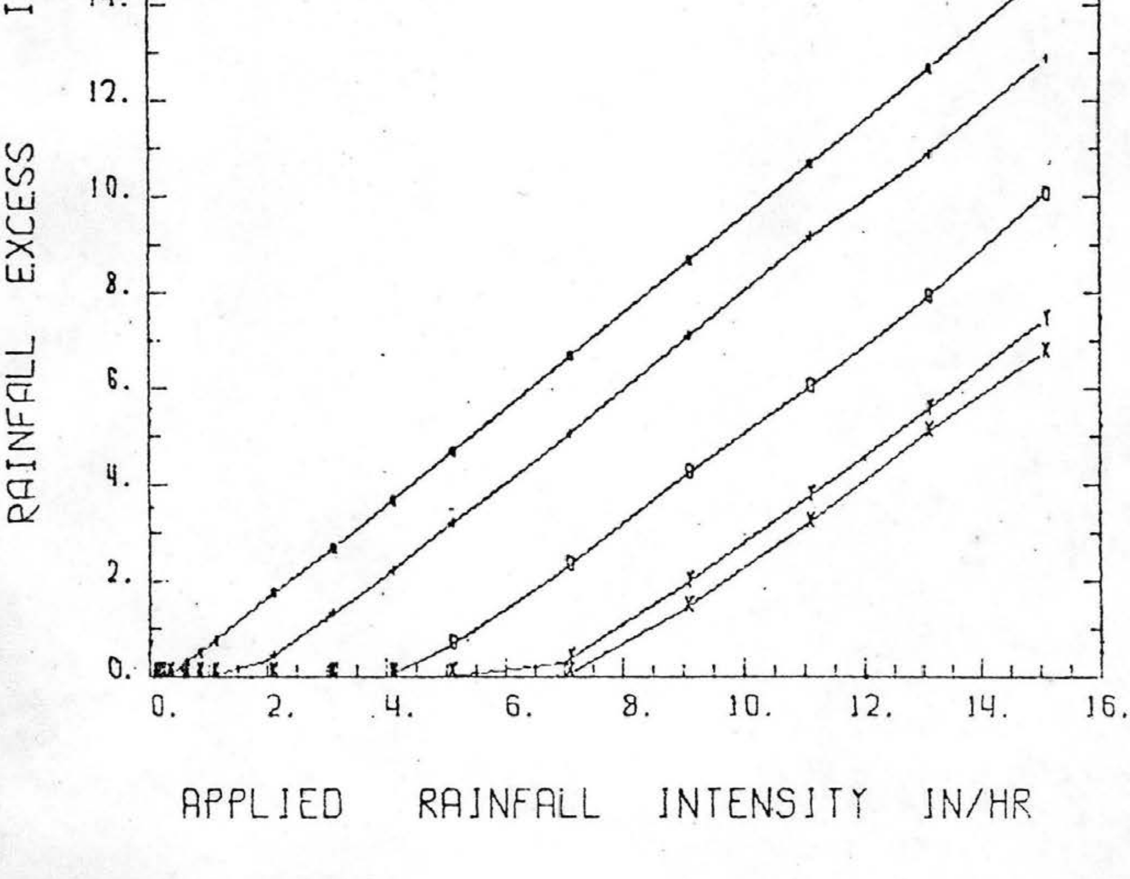

Fig. 4. Rainfall Excess Rate versus Rainfall Intensity for Storm Duration of 30 Minutes

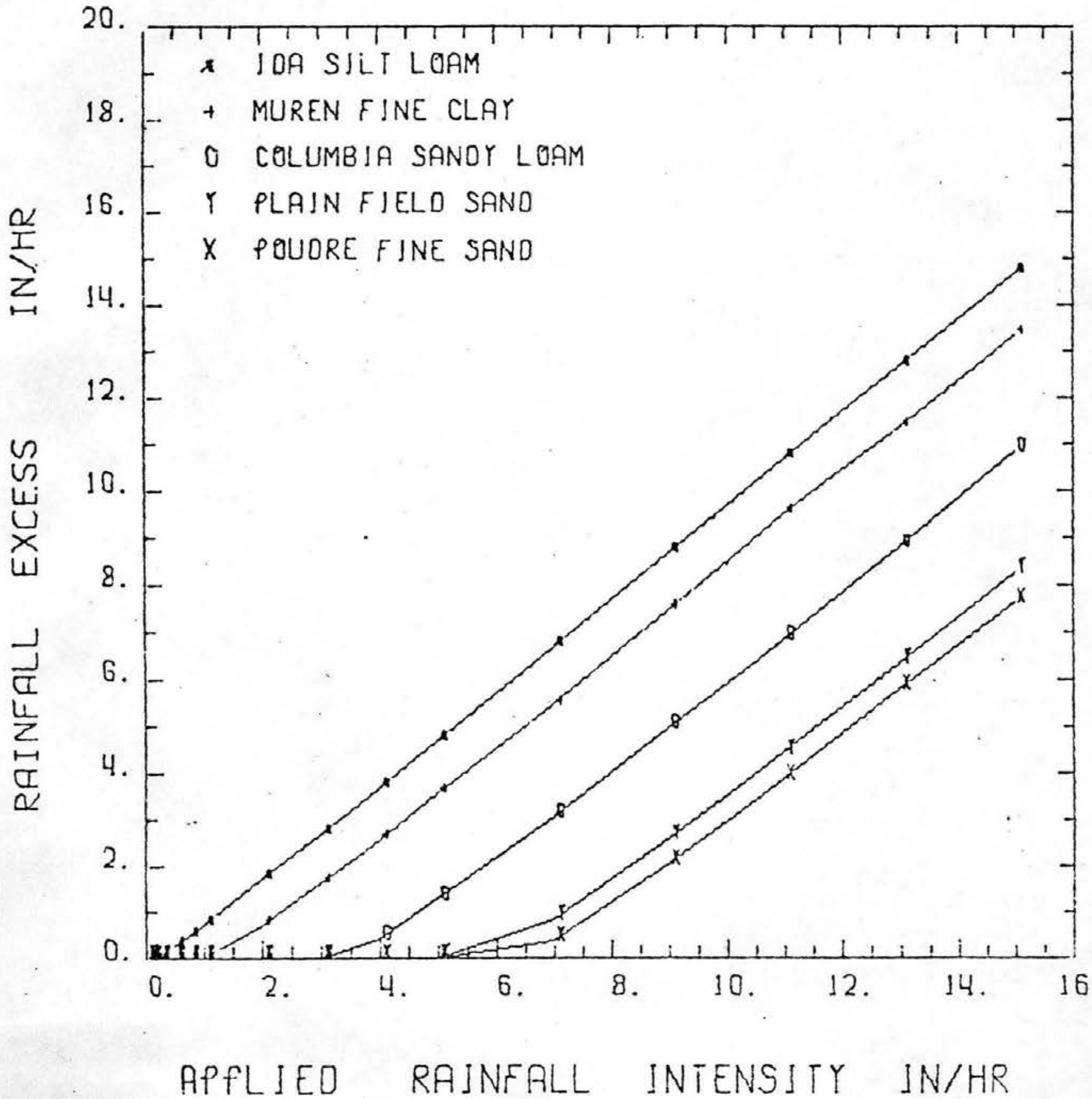

Fig. 5. Rainfall Excess Rate versus Rainfall Intensity for Storm Duration of 60 Minutes

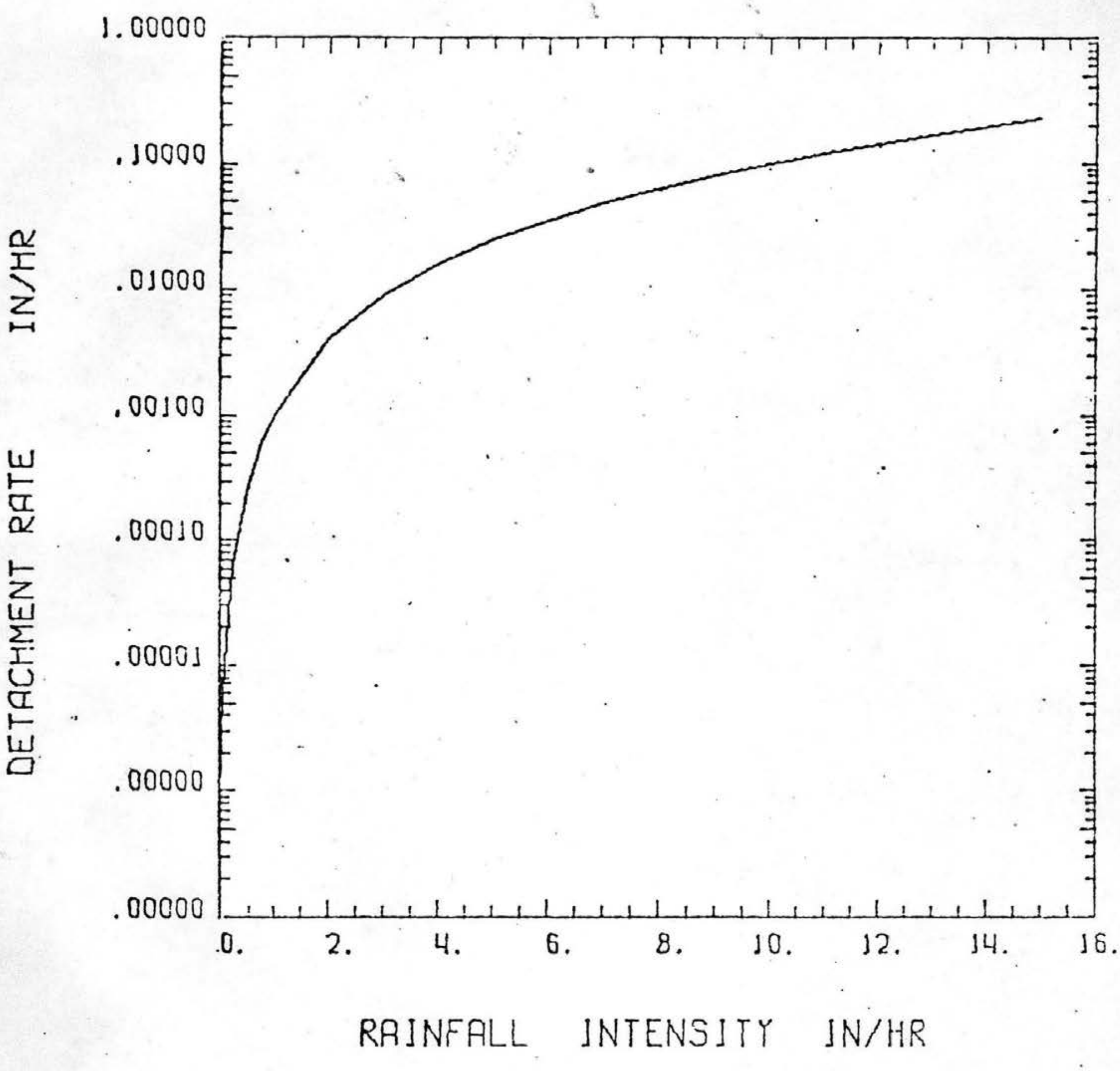

Fig. 6. Assumed Soil Detachment Rate by Raindrop Splash

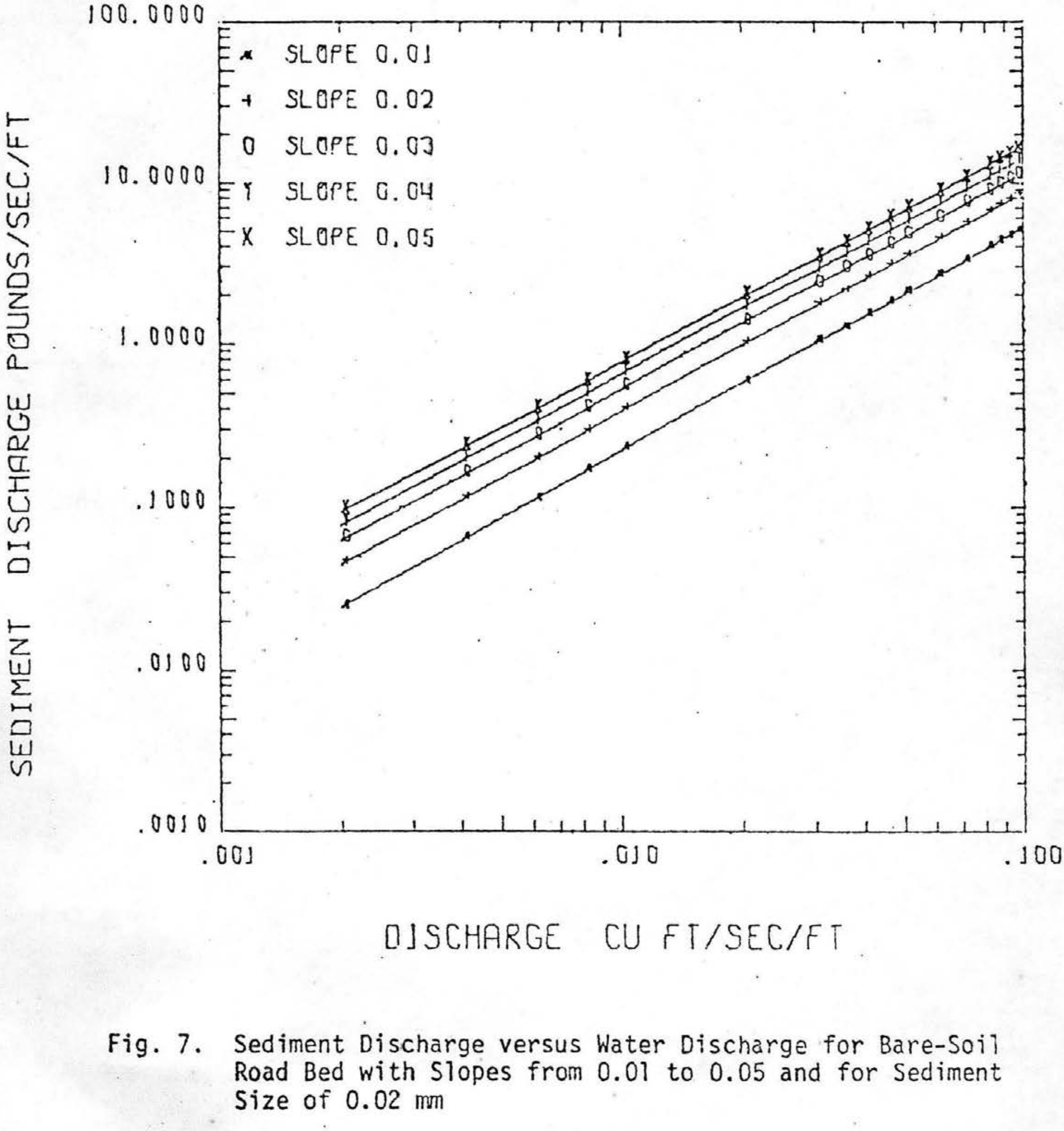

Fig. 7. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.01 to 0.05 and for Sediment Size of 0.02 mm

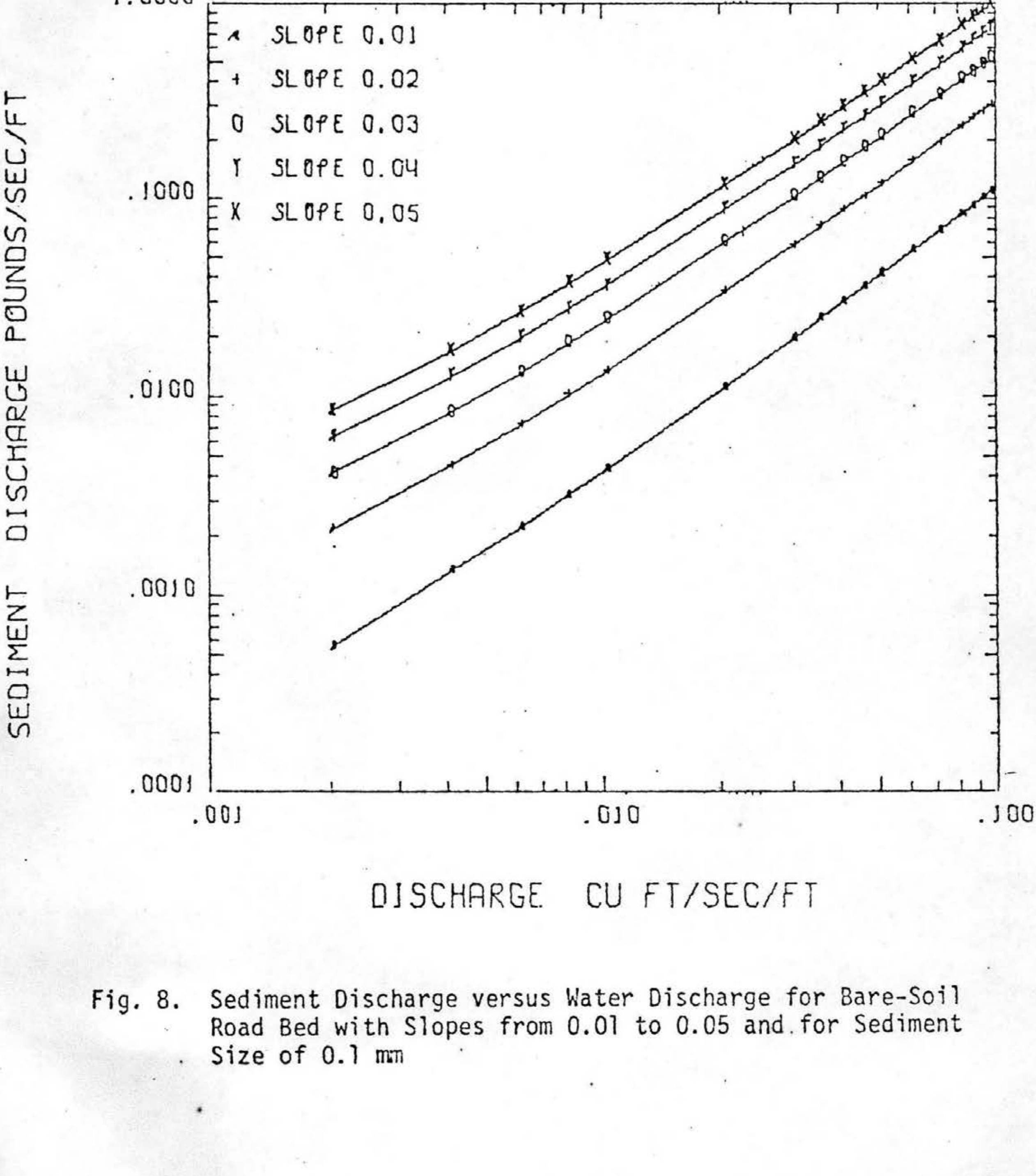

Fig. 8. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.01 to 0.05 and for Sediment Size of 0.1 mm

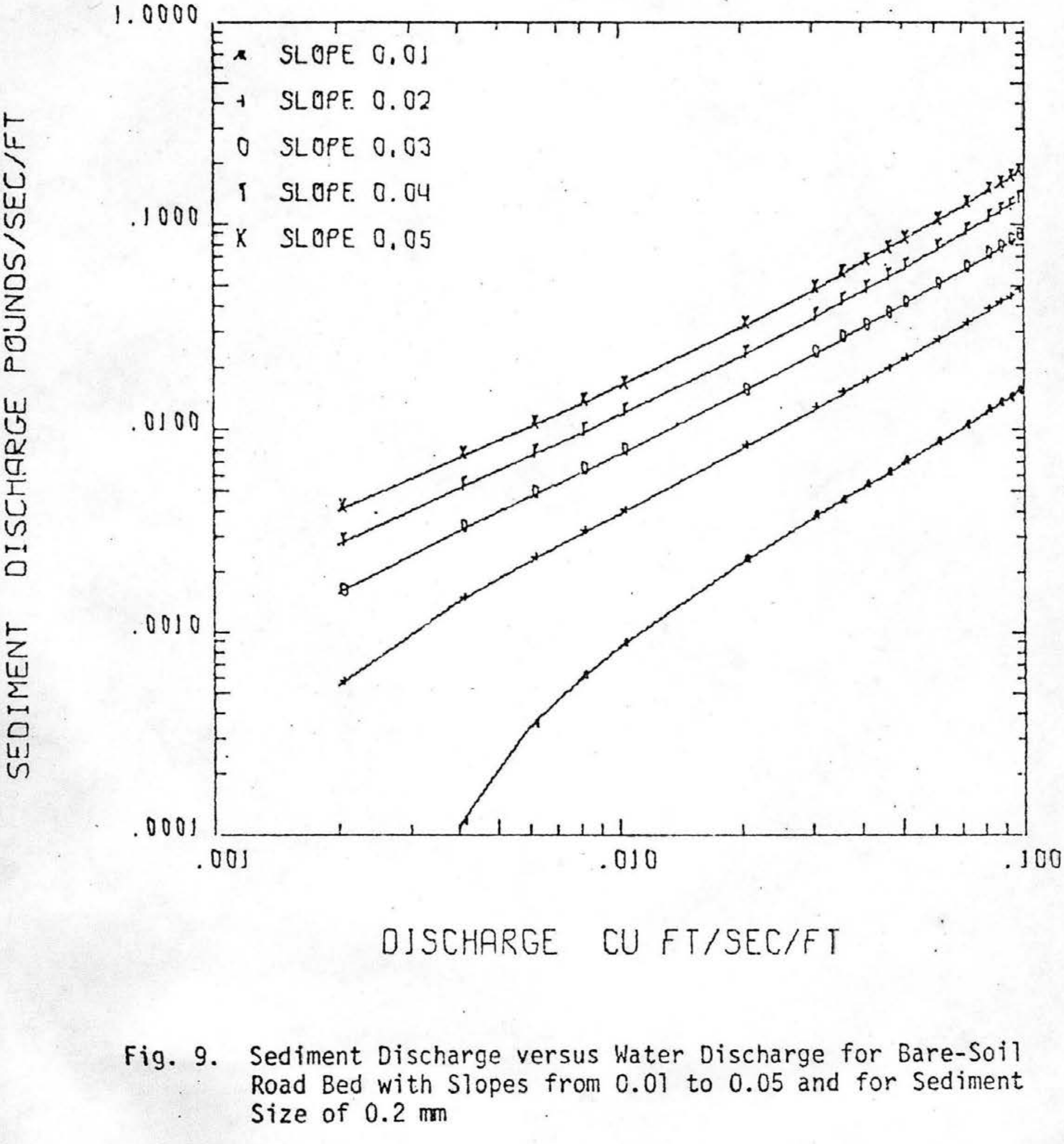

Fig. 9. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.01 to 0.05 and for Sediment Size of 0.2 mm

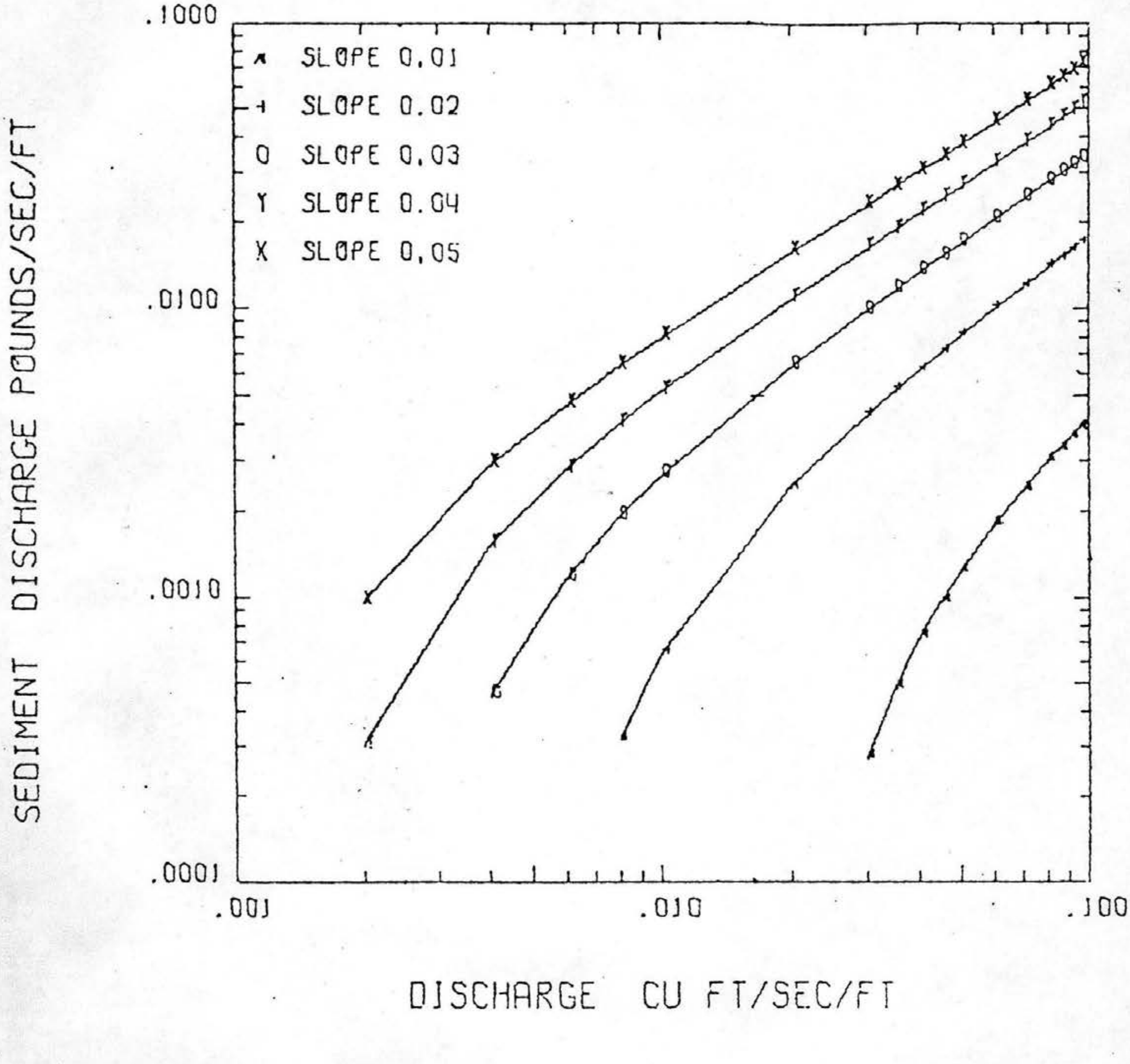

Fig. 10. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.01 to 0.05 and for Sediment Size of 0.4 mm

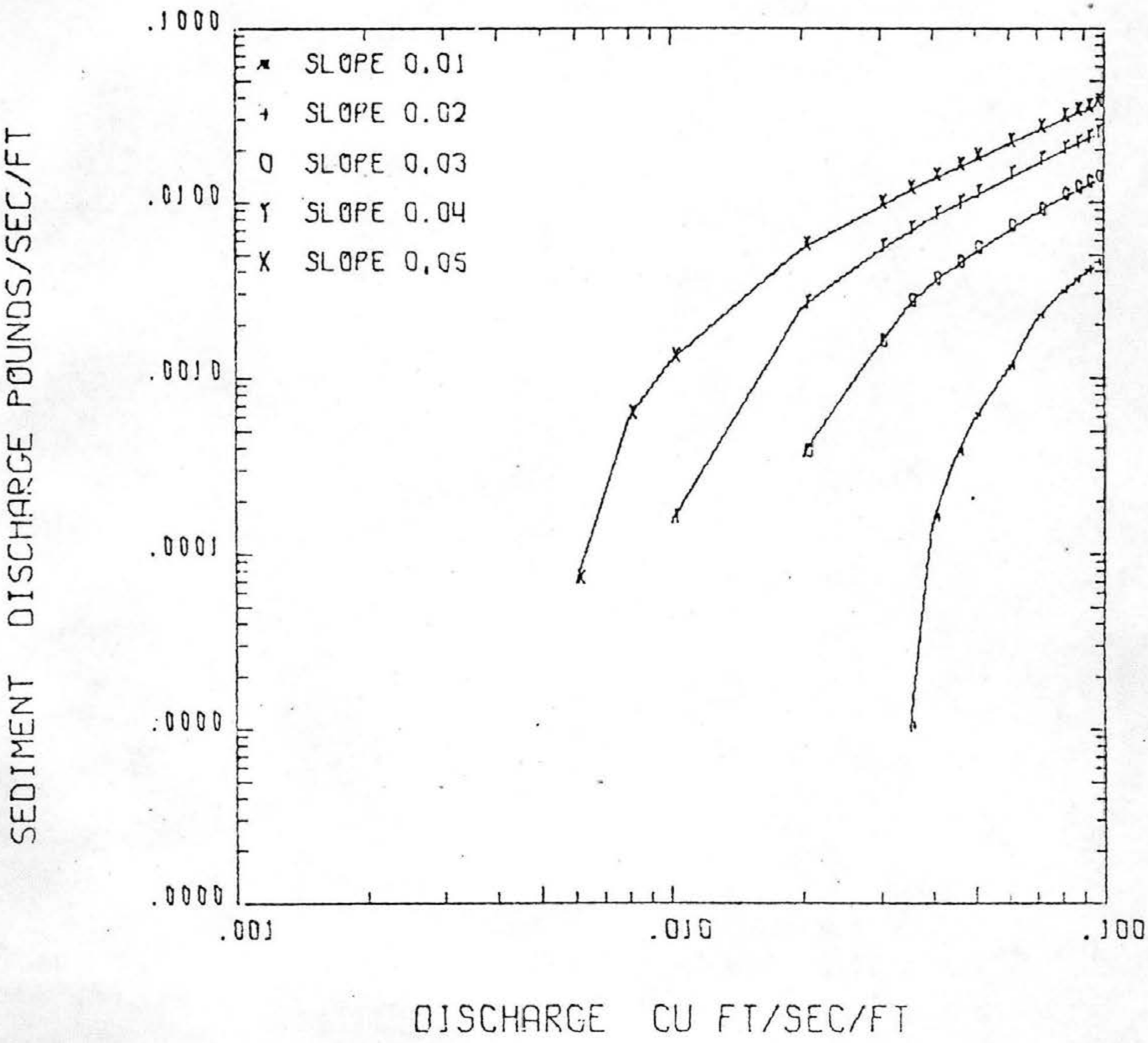

Fig. 11. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.01 to 0.05 and for Sediment Size of 0.75 mm

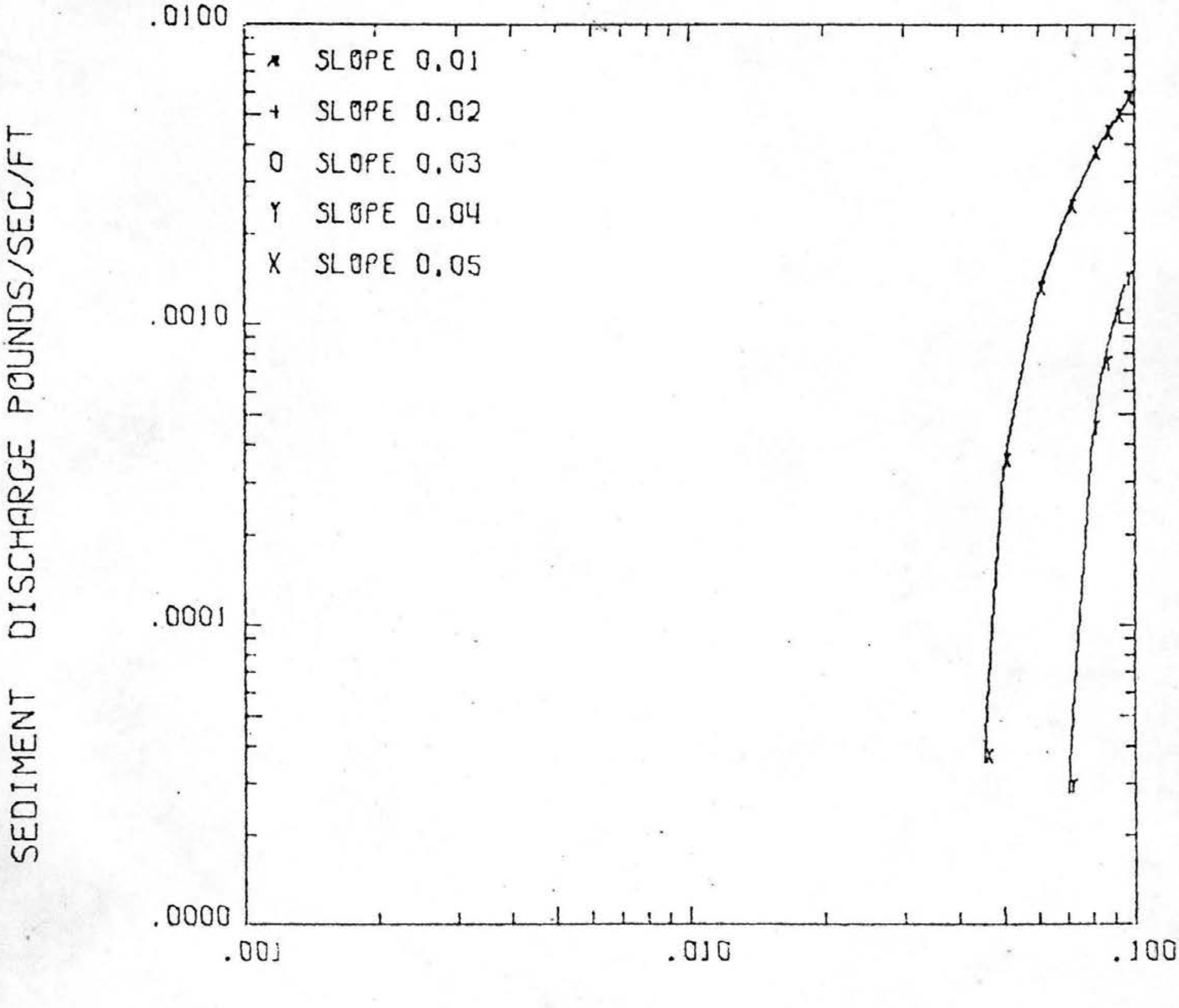

Fig. 12. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.01 to 0.05 and for Sediment Size of 1.5 mm

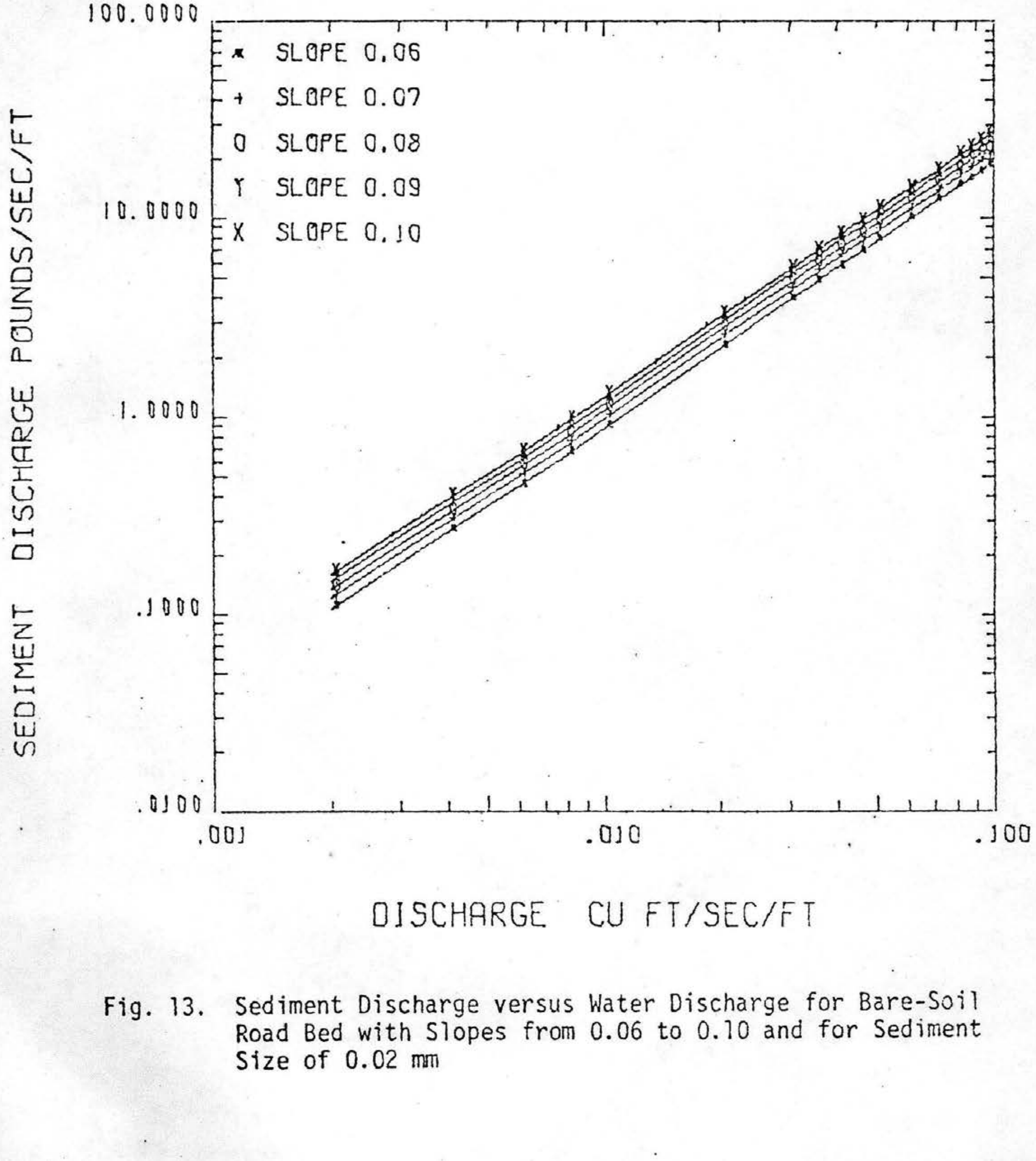

Fig. 13. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.06 to 0.10 and for Sediment Size of 0.02 mm

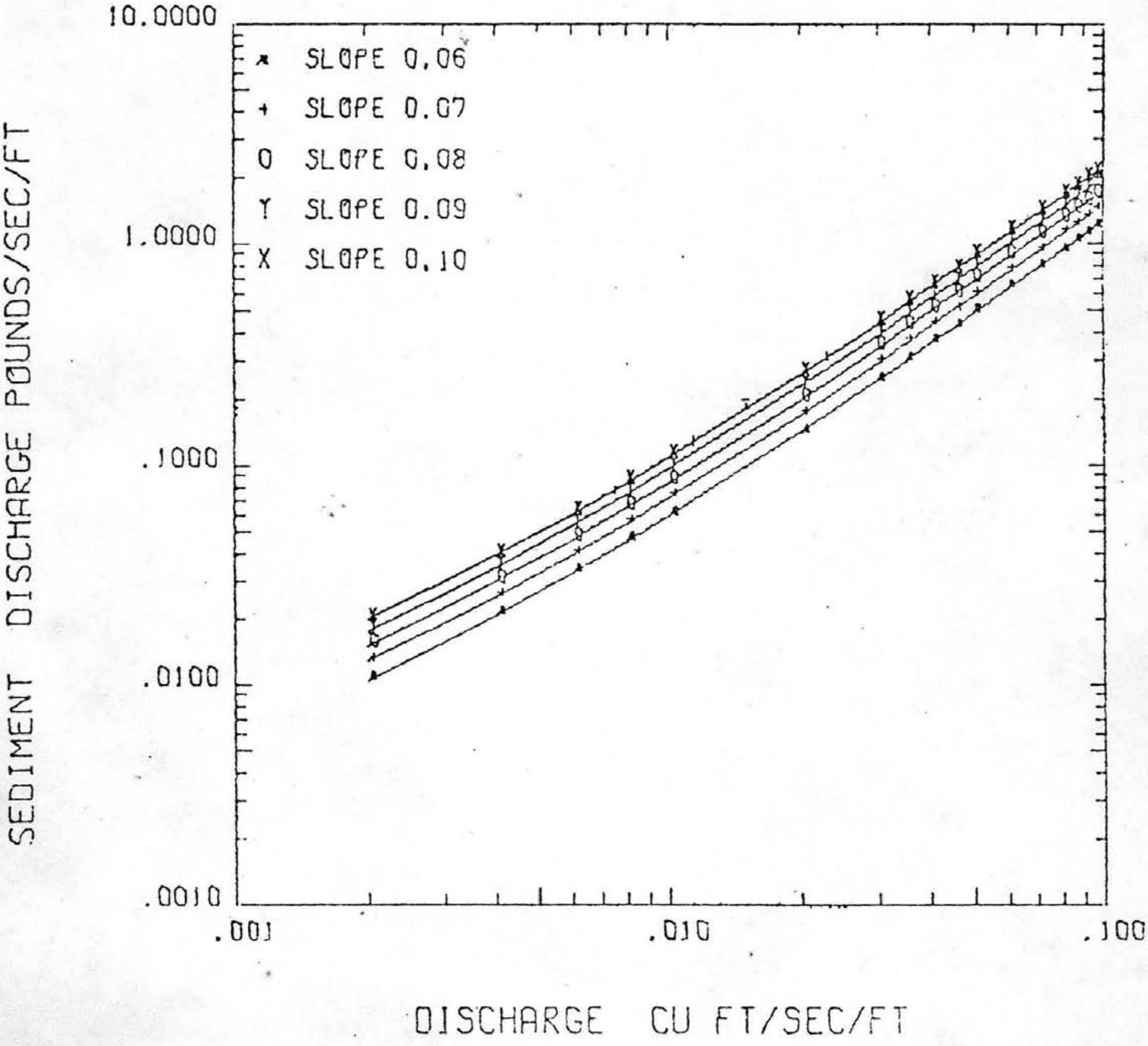

Fig. 14 Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.06 to 0.10 and for Sediment Size of 0.1 mm

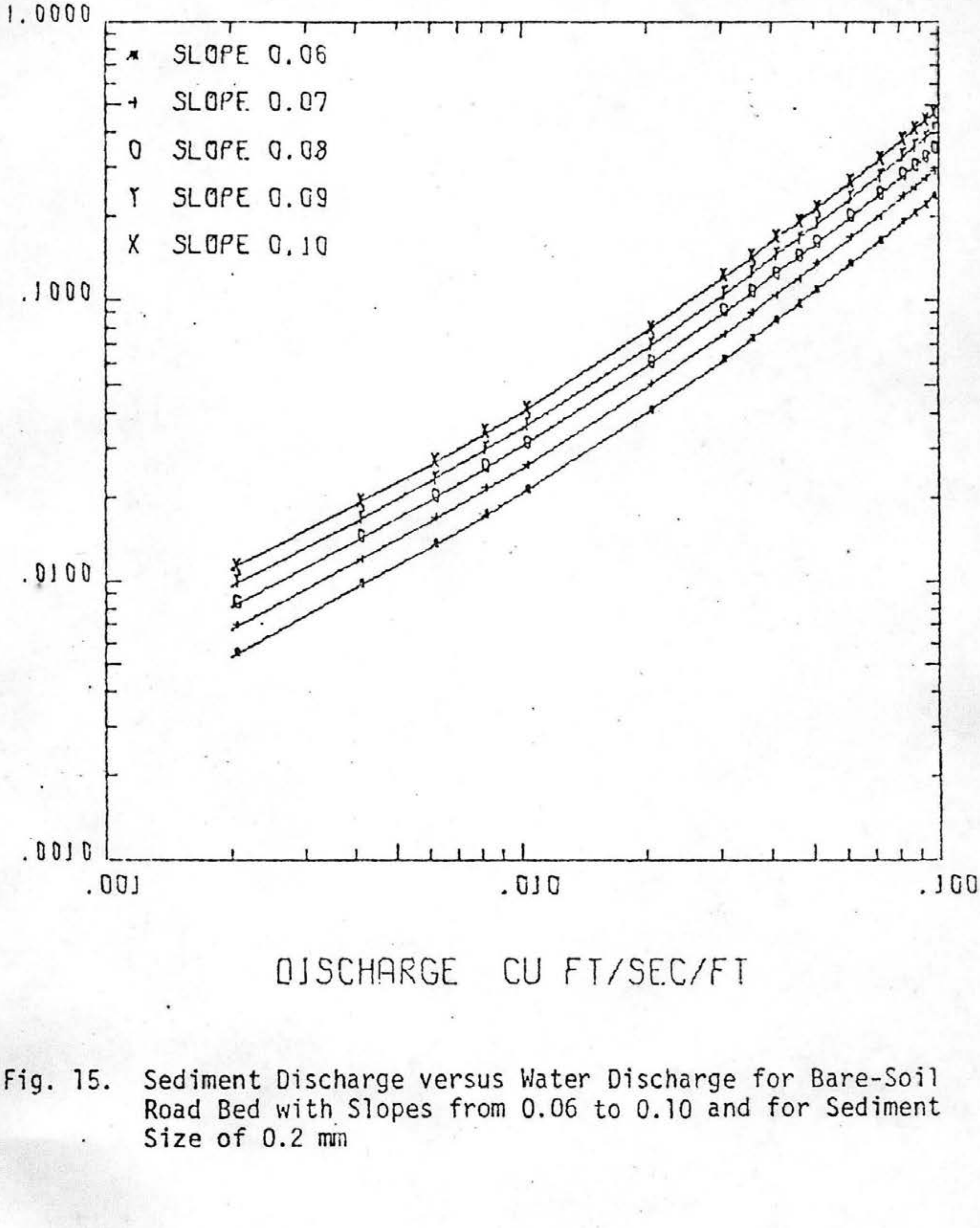

Fig. 15. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.06 to 0.10 and for Sediment Size of 0.2 mm

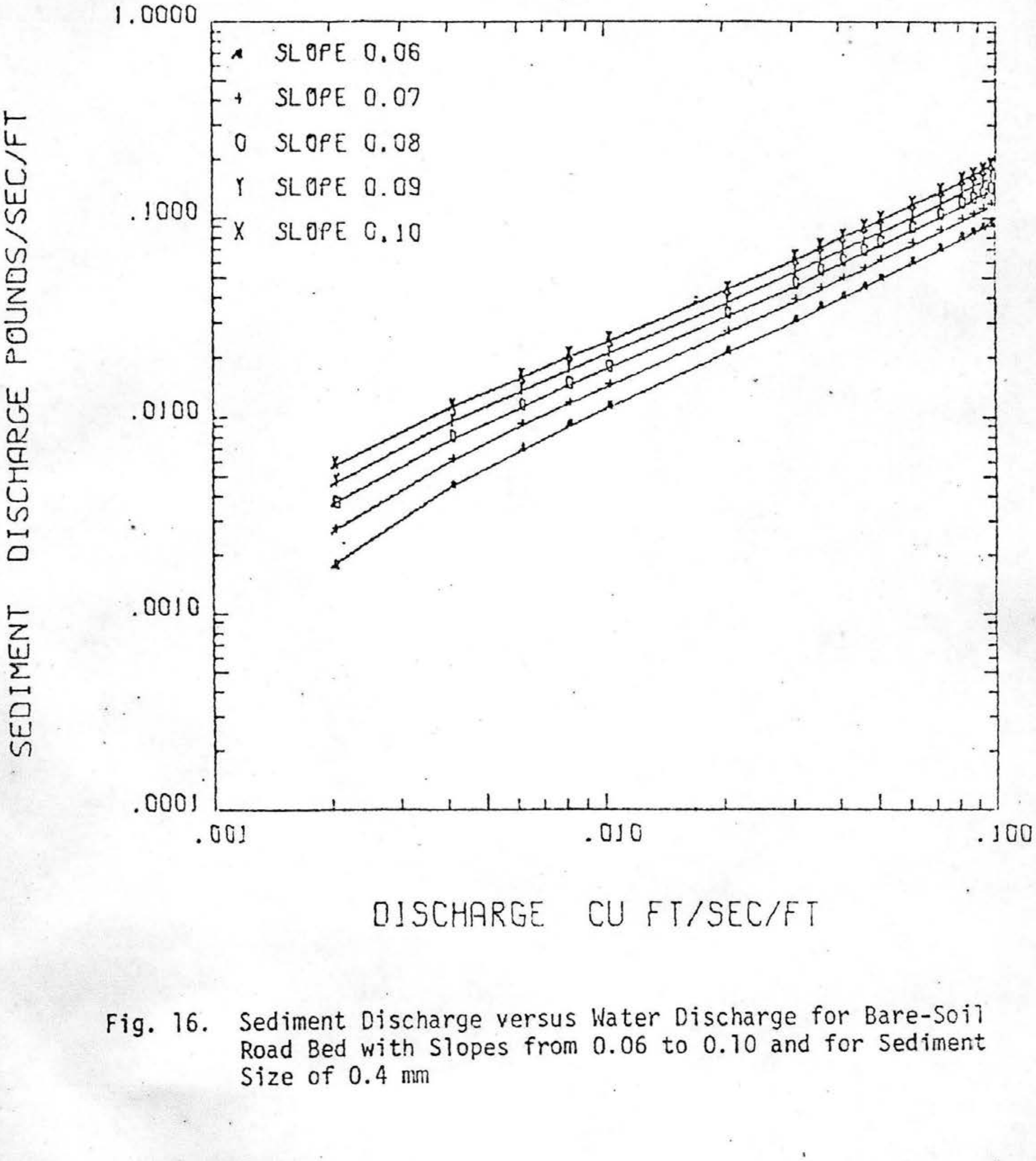

Fig. 16. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.06 to 0.10 and for Sediment Size of 0.4 mm

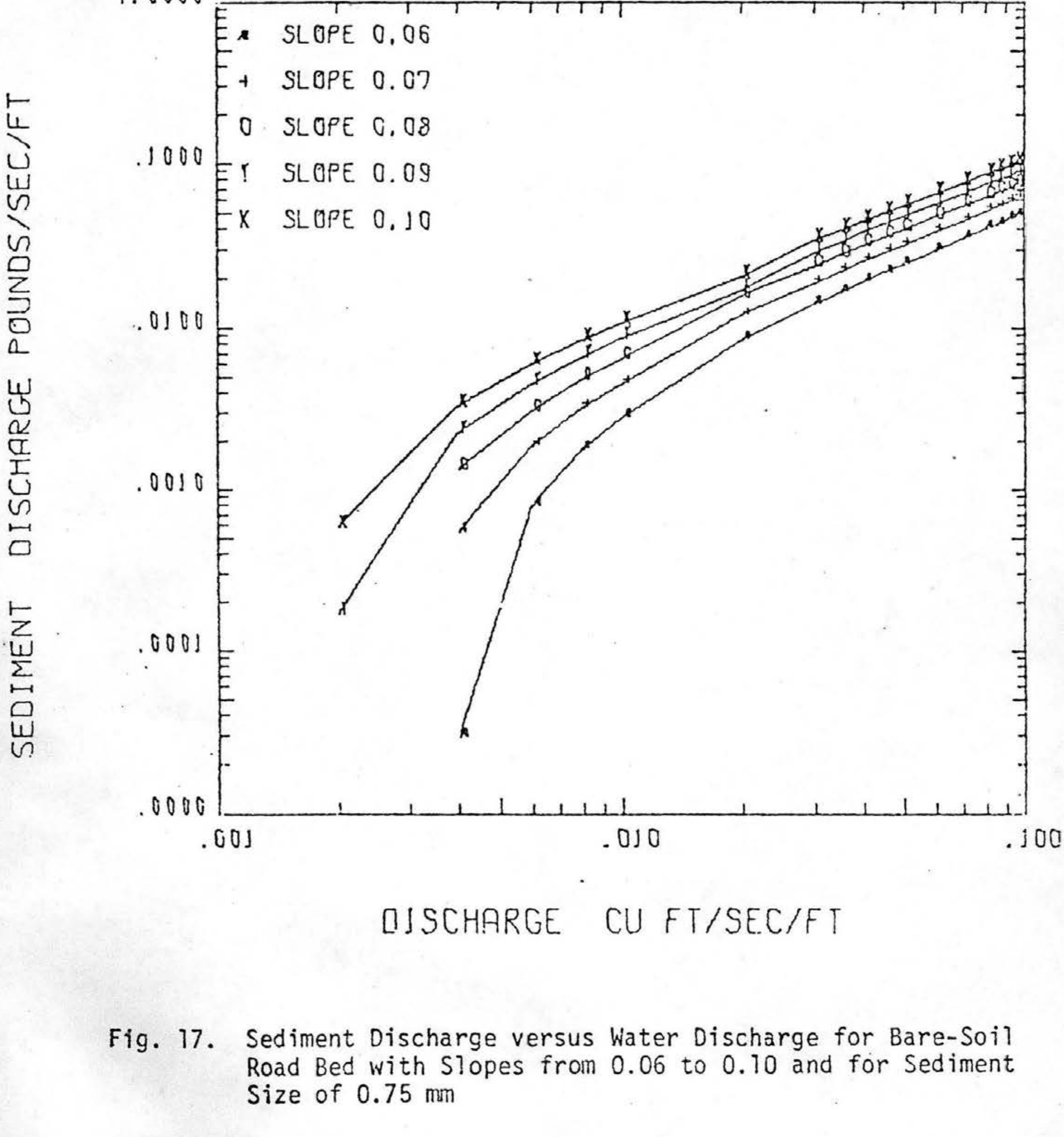

Fig. 17. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.06 to 0.10 and for Sediment Size of 0.75 mm

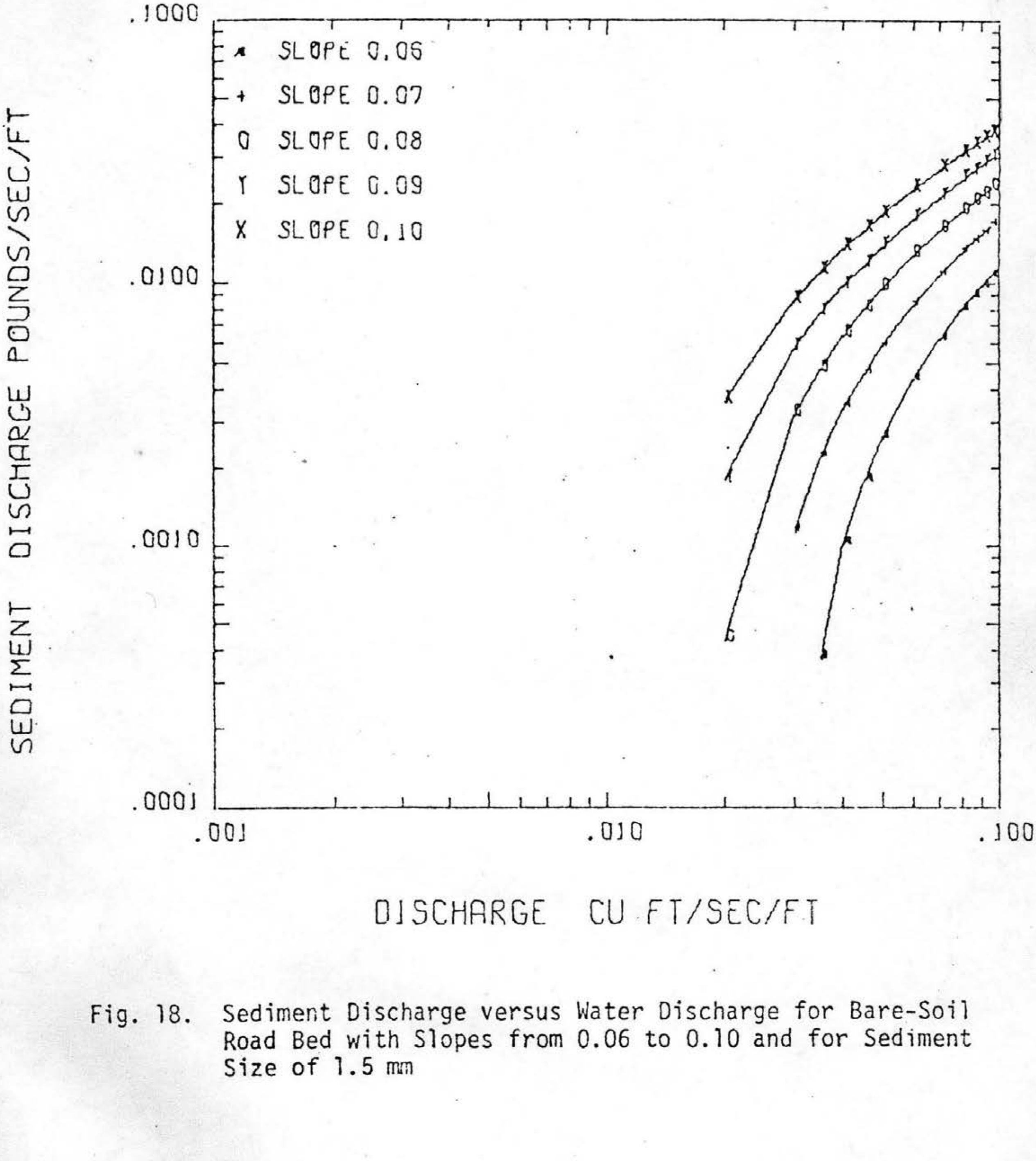

Fig. 18. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.06 to 0.10 and for Sediment Size of 1.5 mm

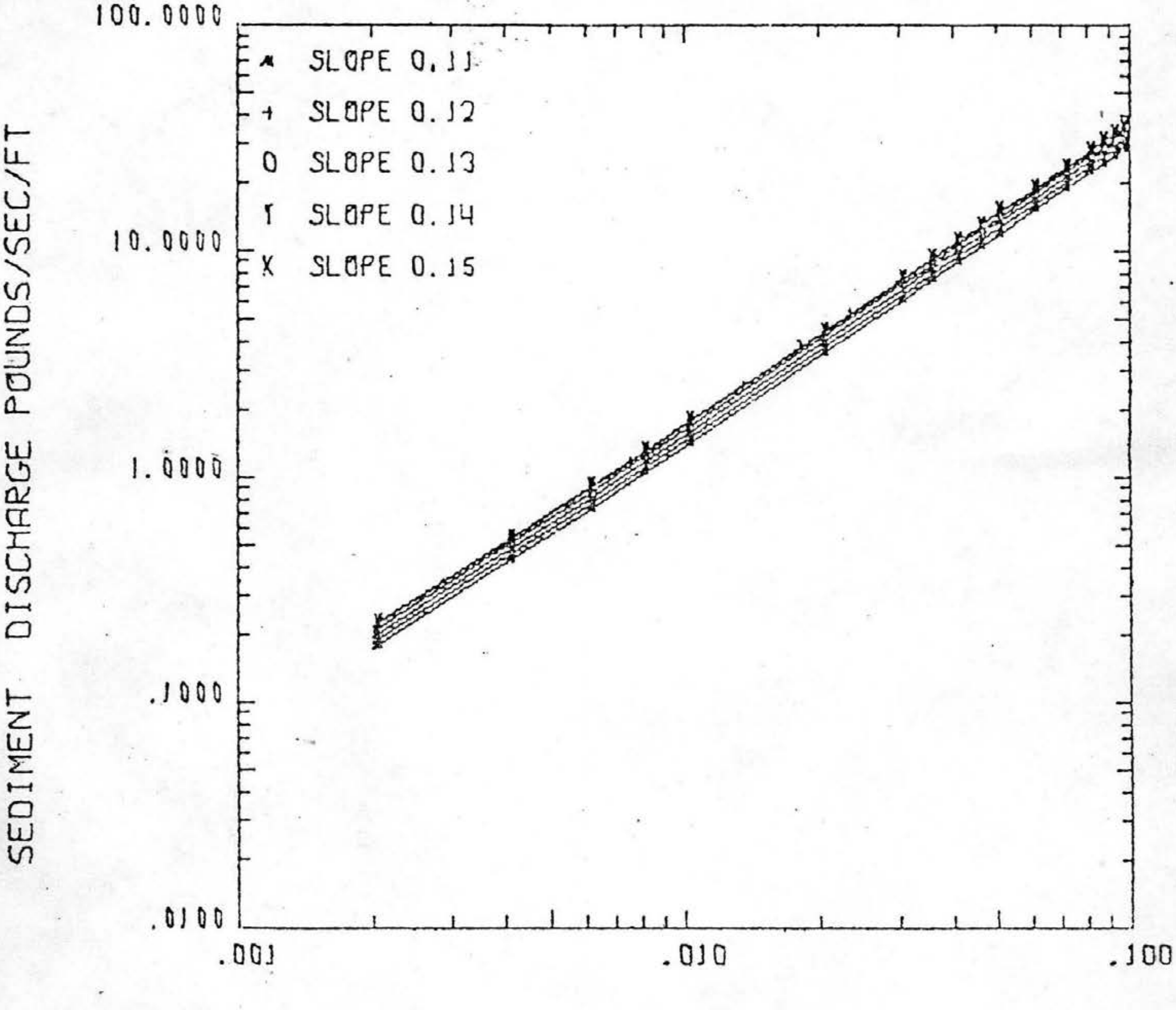

Fig. 19. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.11 to 0.15 and for Sediment Size of 0.02 mm

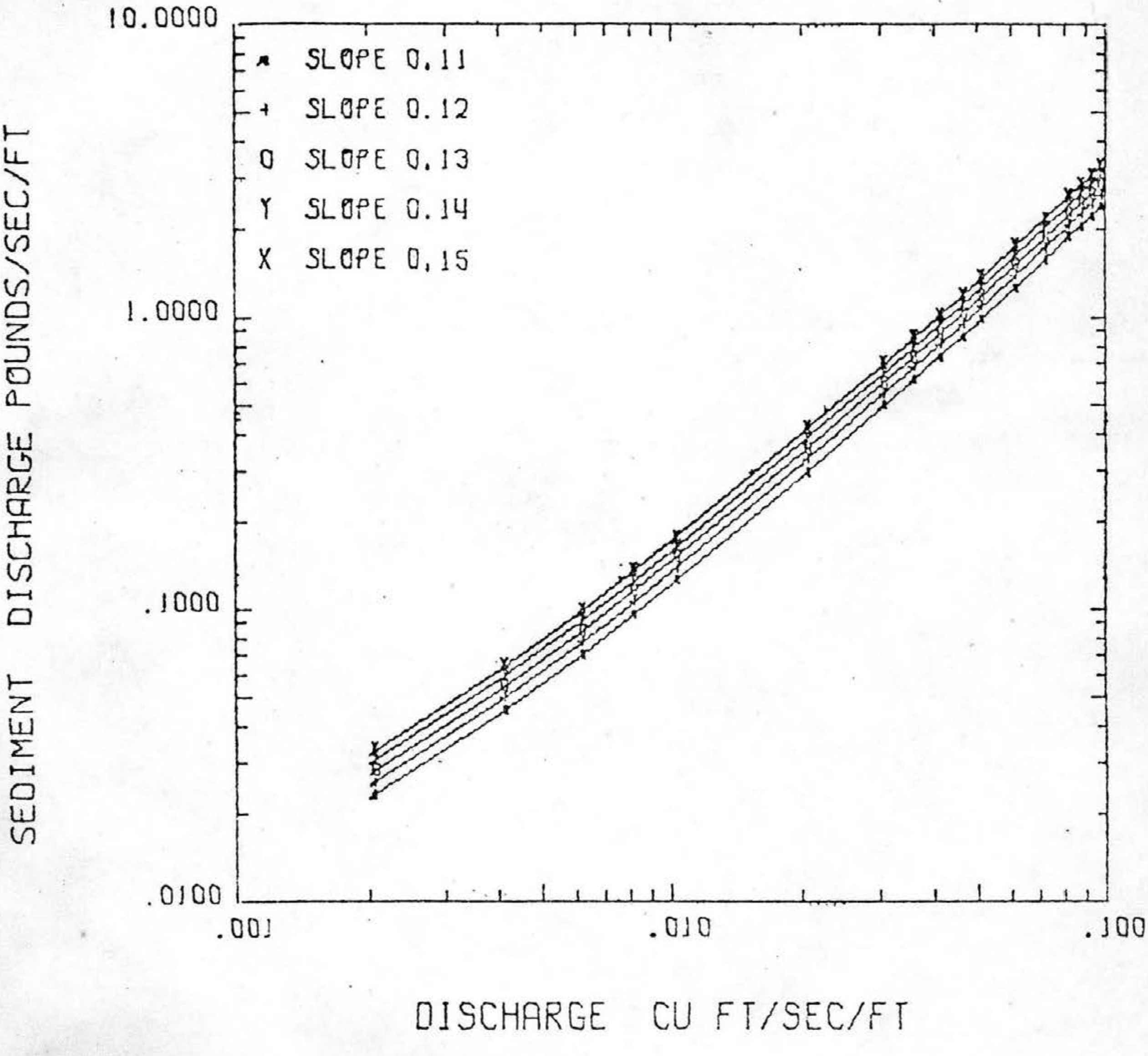

Fig. 20. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.11 to 0.15 and for Sediment Size of 0.1 mm

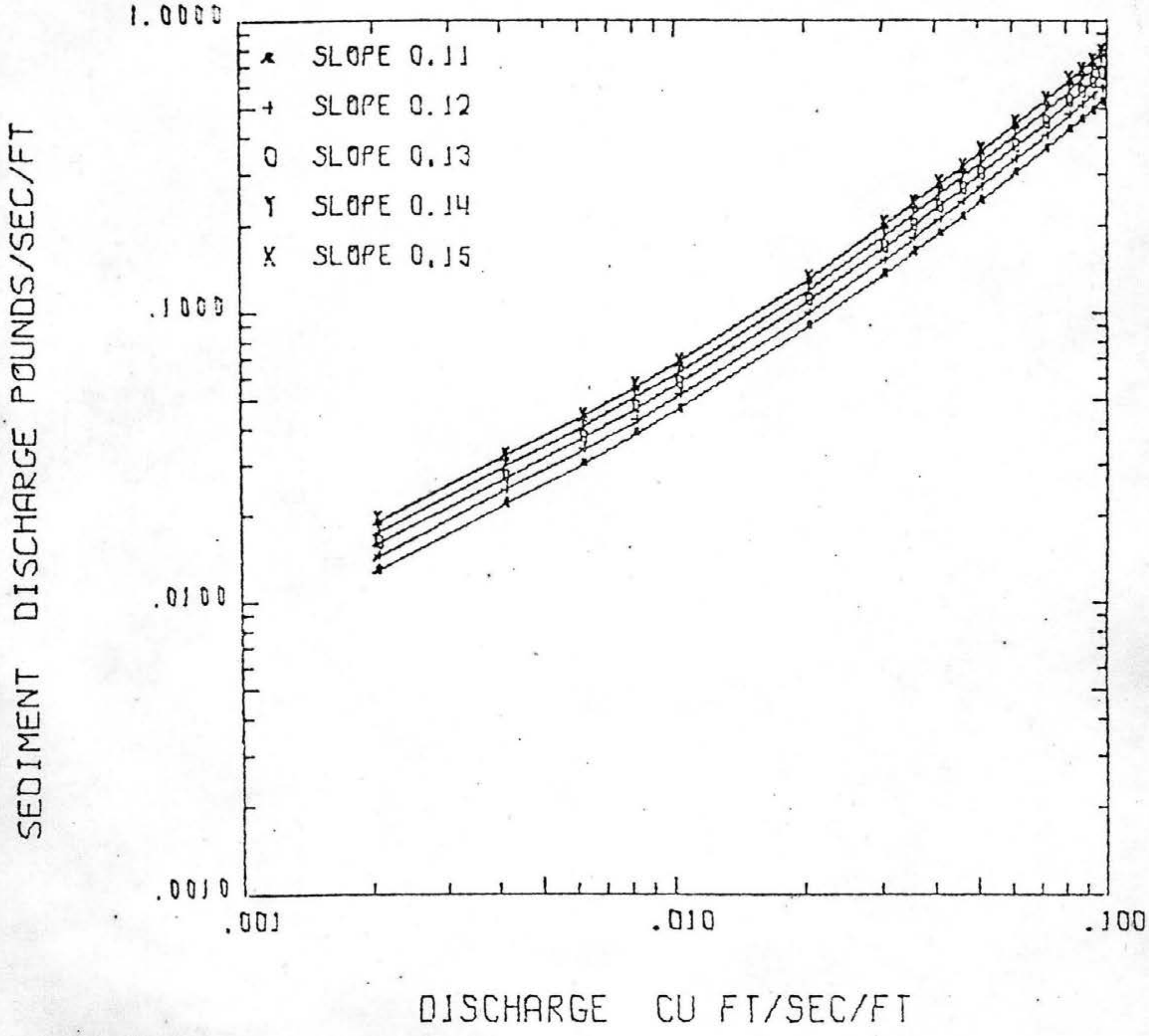

Fig. 21. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.11 to 0.15 and for Sediment Size of 0.2 mm

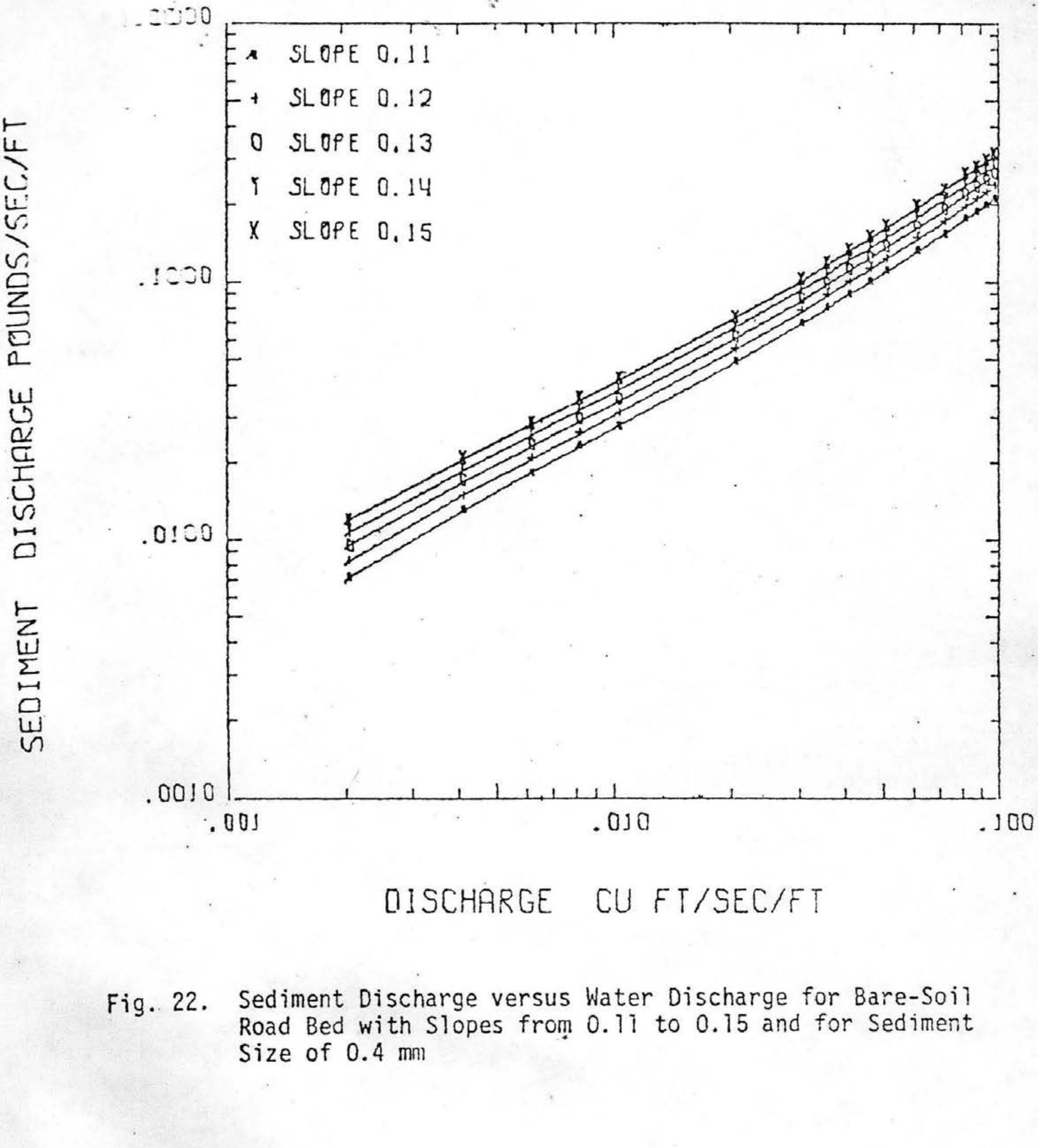

Fig. 22. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.11 to 0.15 and for Sediment Size of 0.4 mm

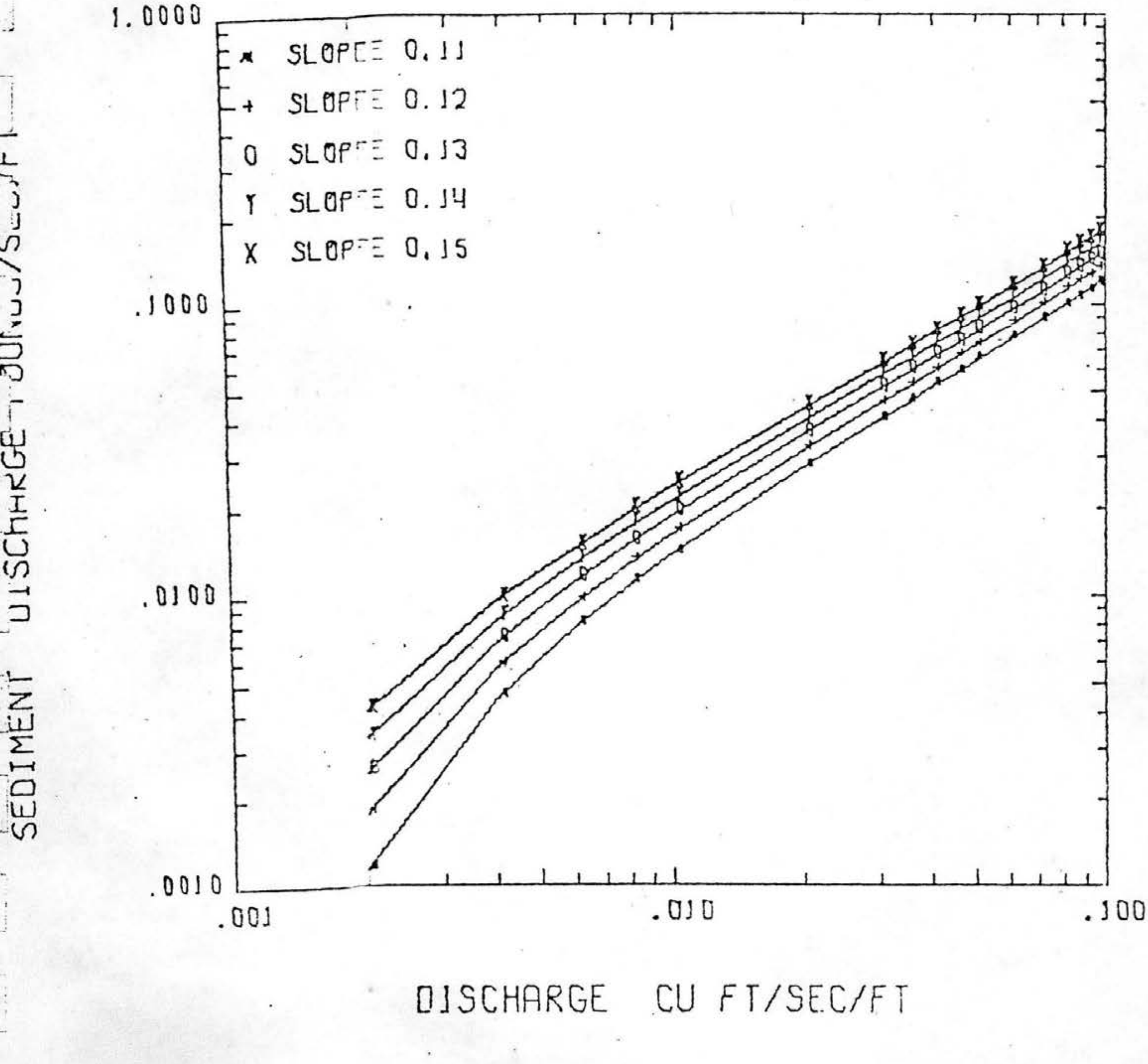

Fig. 23. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.11 to 0.15 and for Sediment Size of 0.75 mm

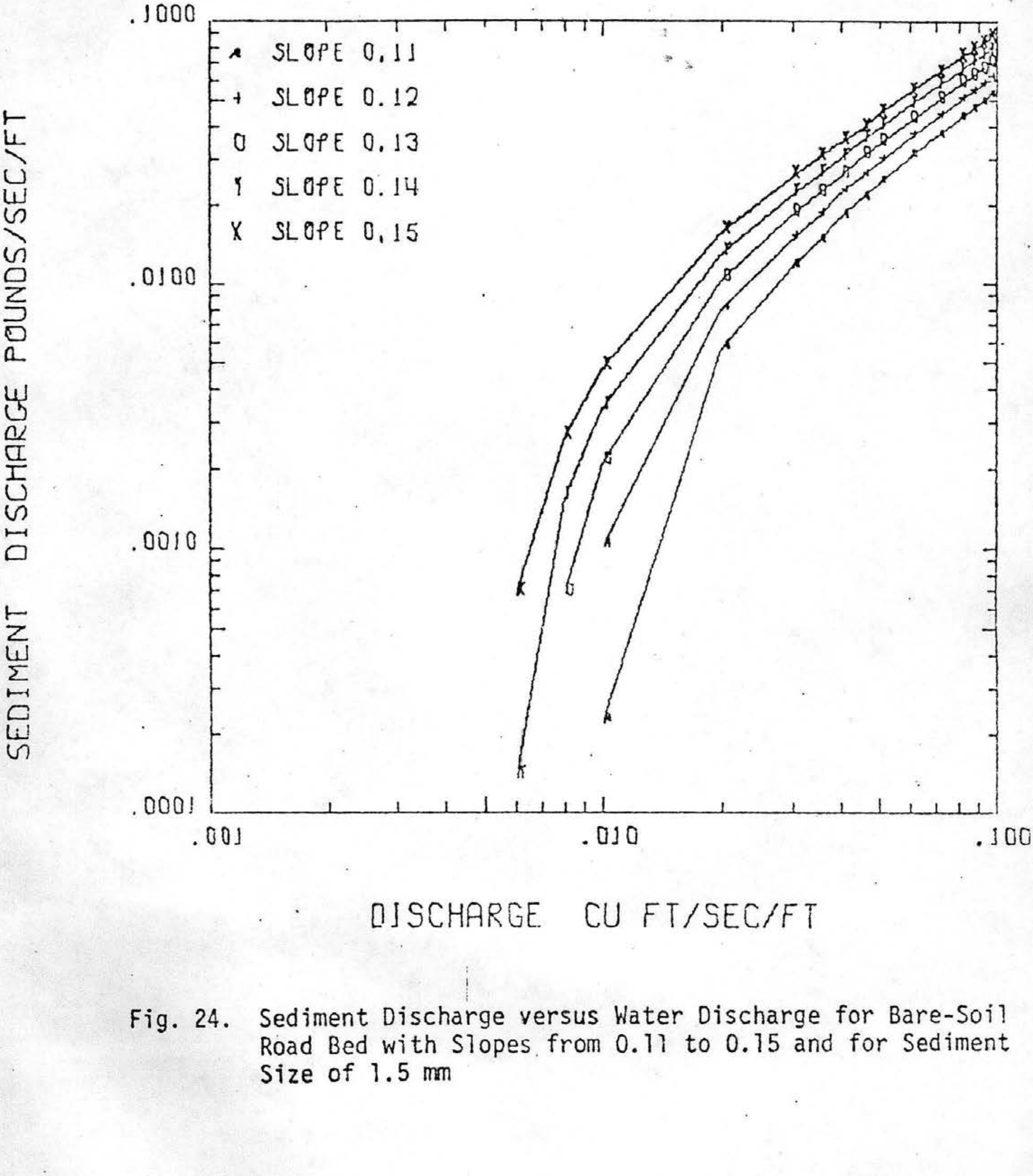

Fig. 24. Sediment Discharge versus Water Discharge for Bare-Soil Road Bed with Slopes from 0.11 to 0.15 and for Sediment Size of 1.5 mm

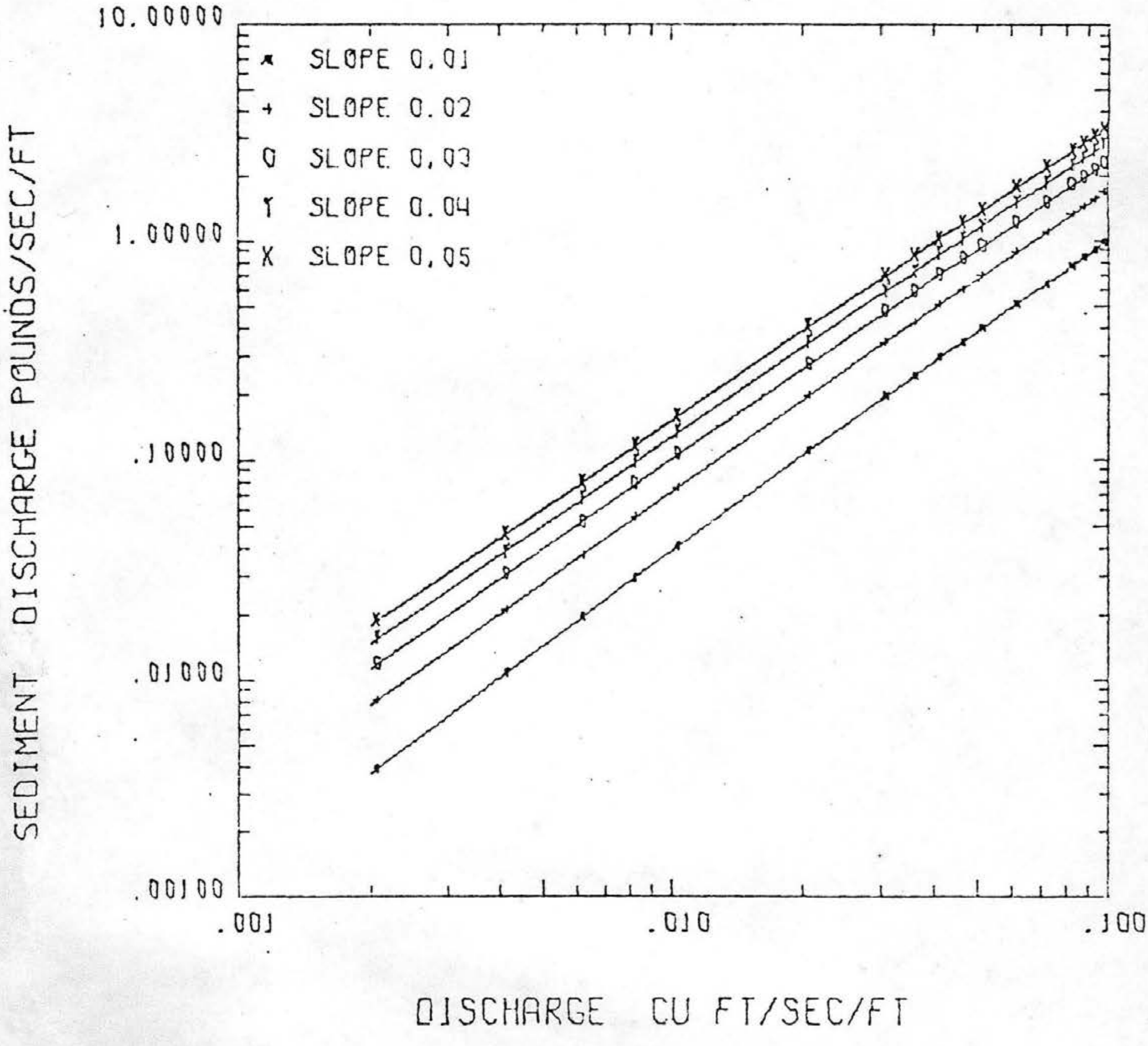

Fig. 25. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.01 to 0.05 and for Sediment Size of 0.02 mm

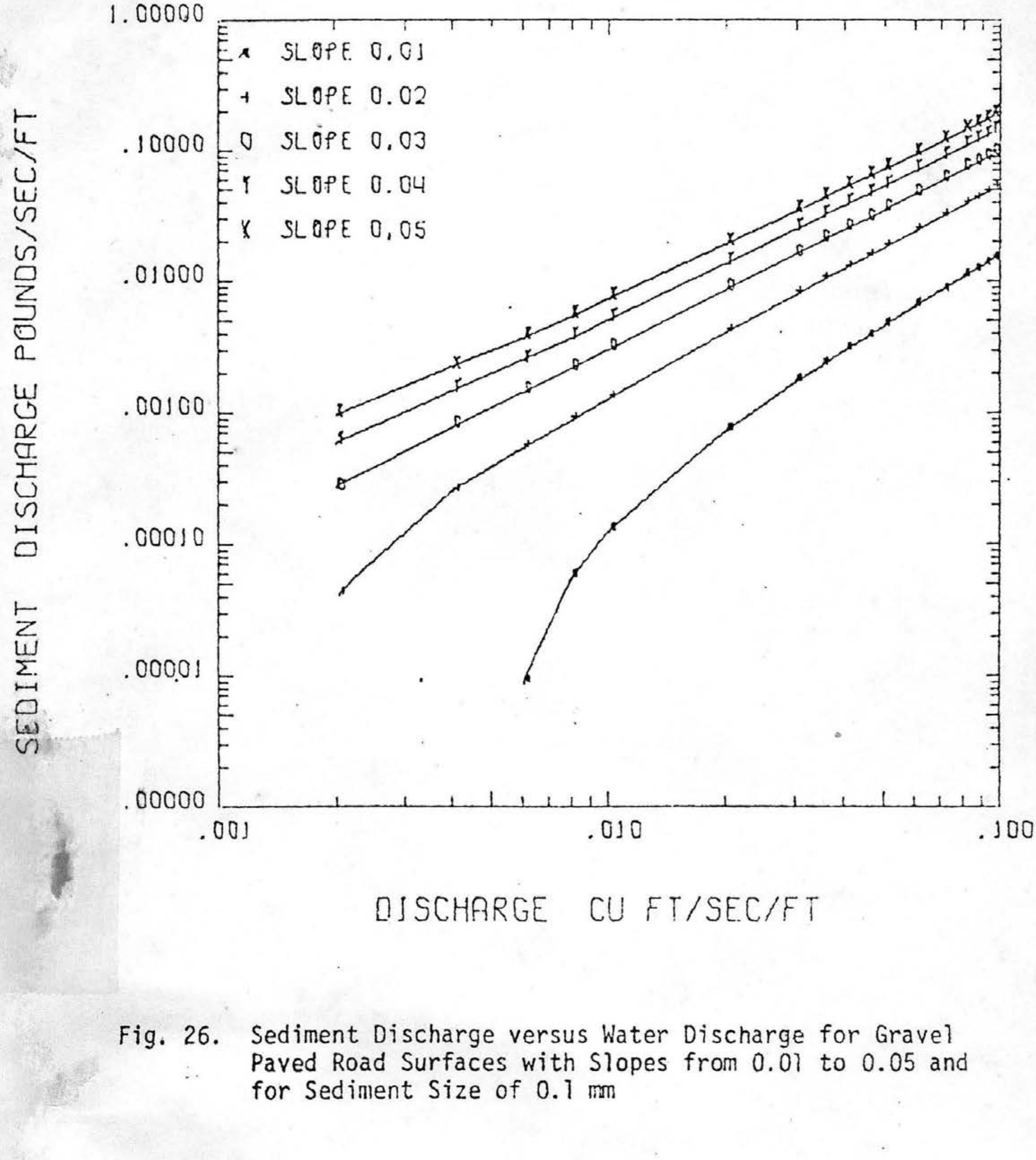

Fig. 26. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.01 to 0.05 and for Sediment Size of 0.1 mm

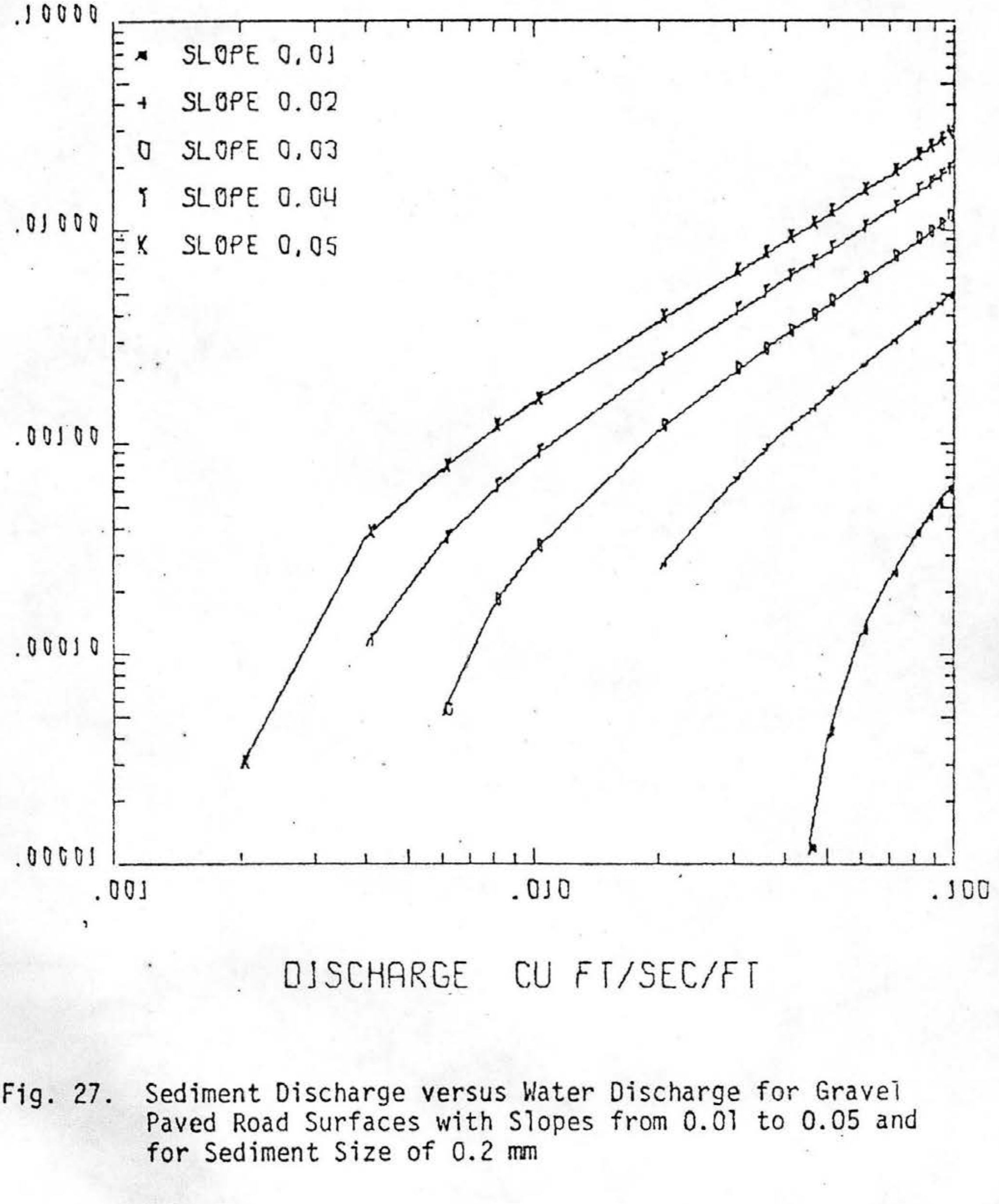

Fig. 27. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.01 to 0.05 and for Sediment Size of 0.2 mm

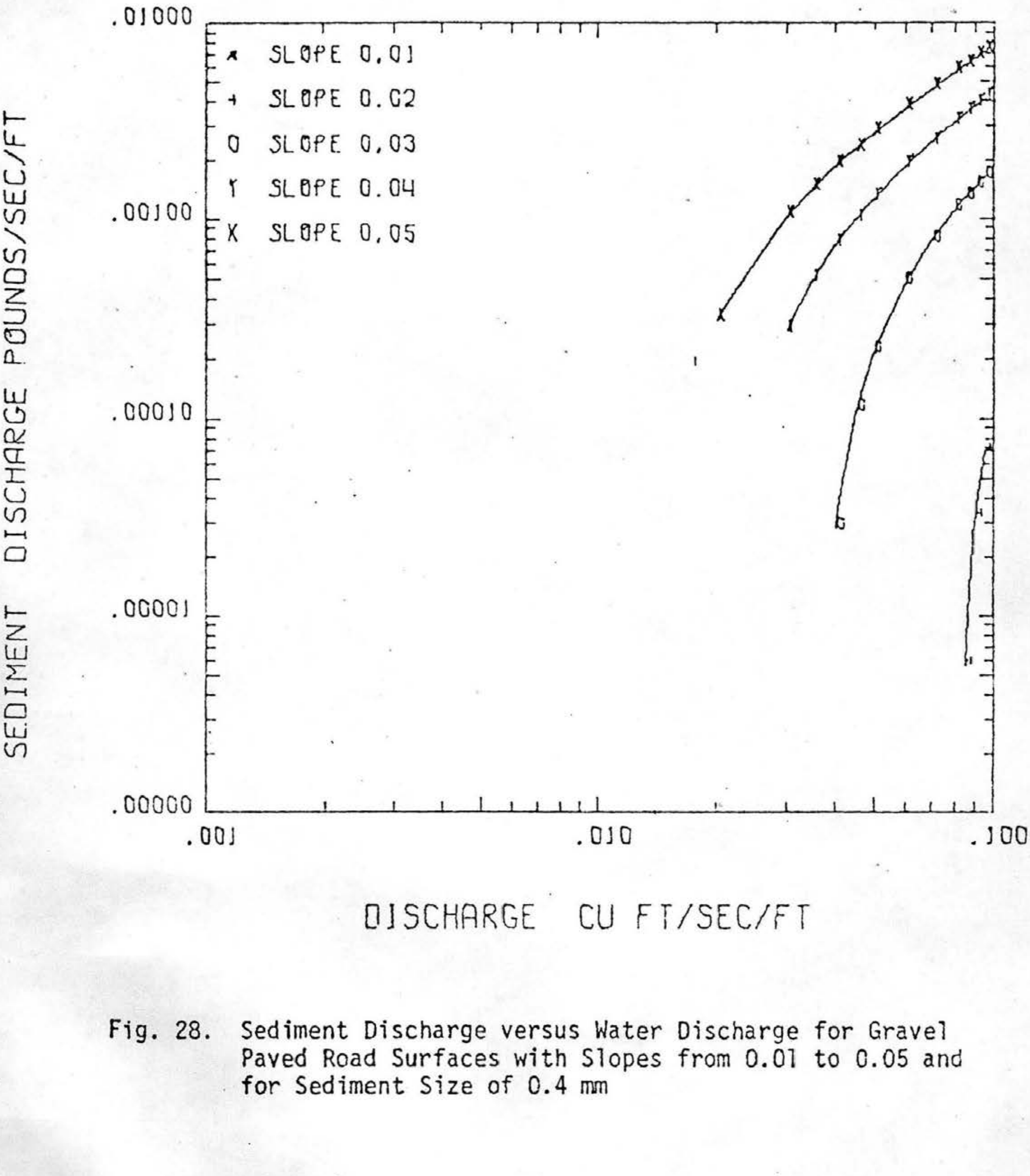

Fig. 28. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.01 to 0.05 and for Sediment Size of 0.4 mm

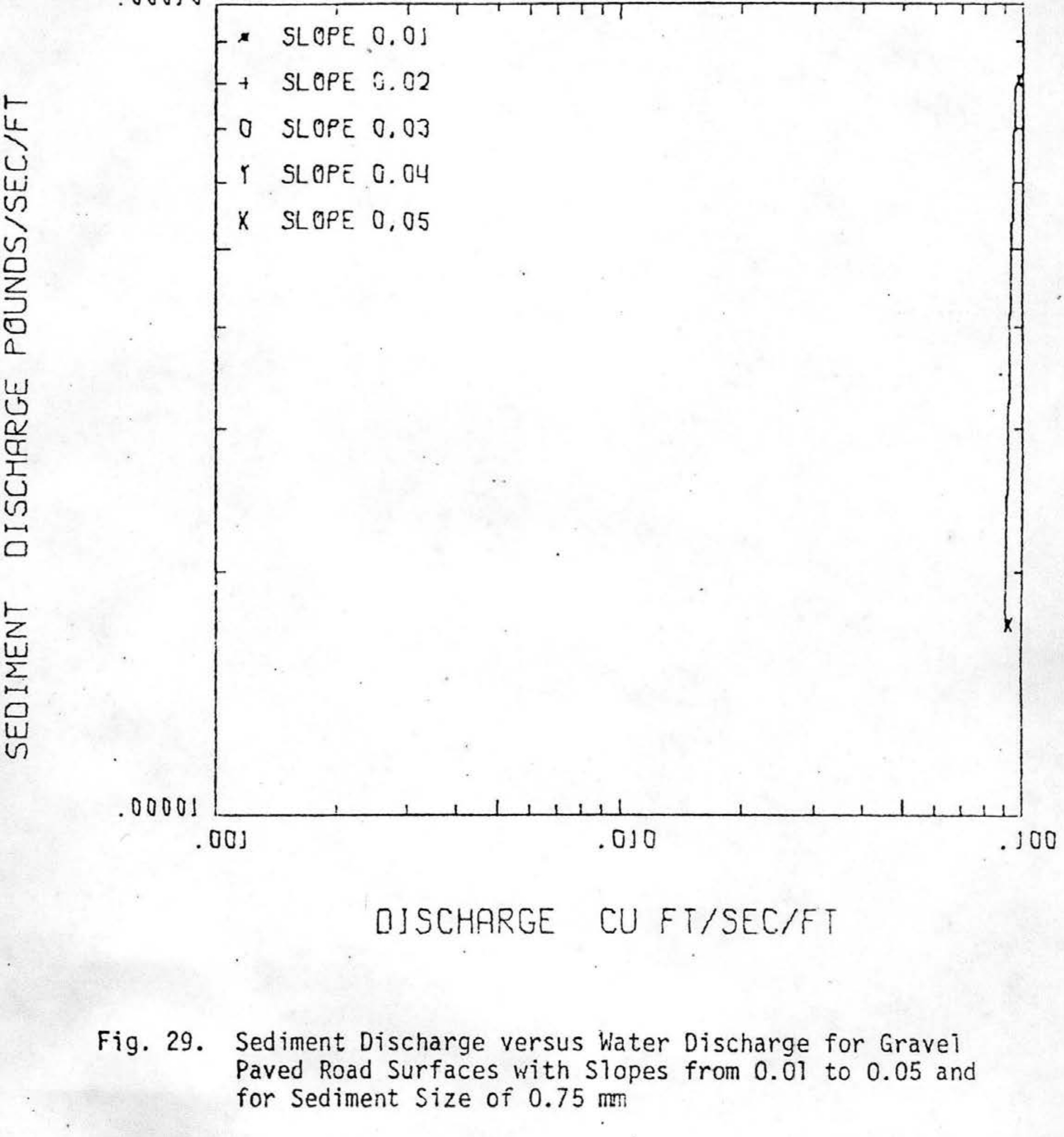

Fig. 29. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.01 to 0.05 and for Sediment Size of 0.75 mm

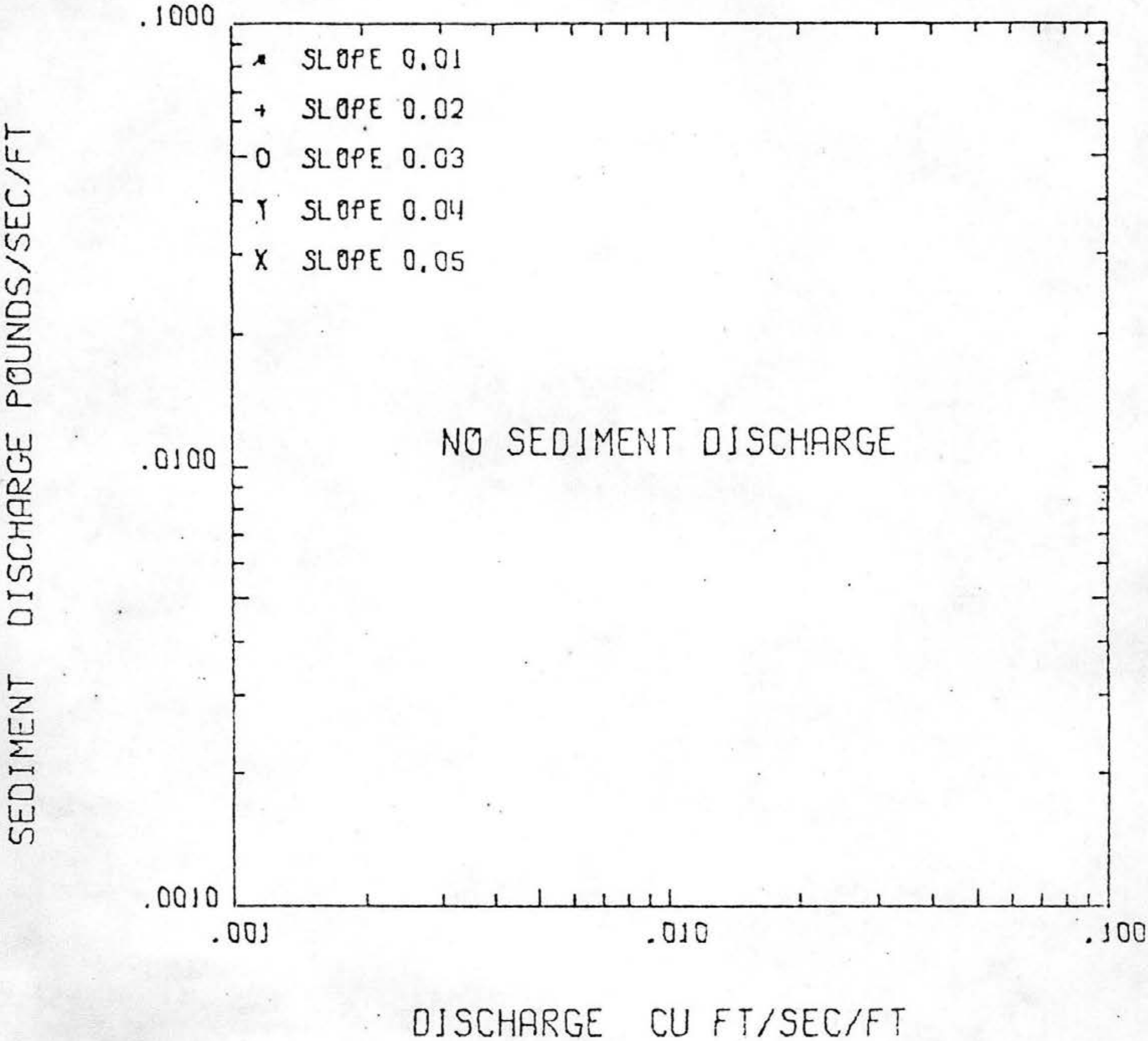

Fig. 30. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.01 to 0.05 and for Sediment Size of 1.5 mm

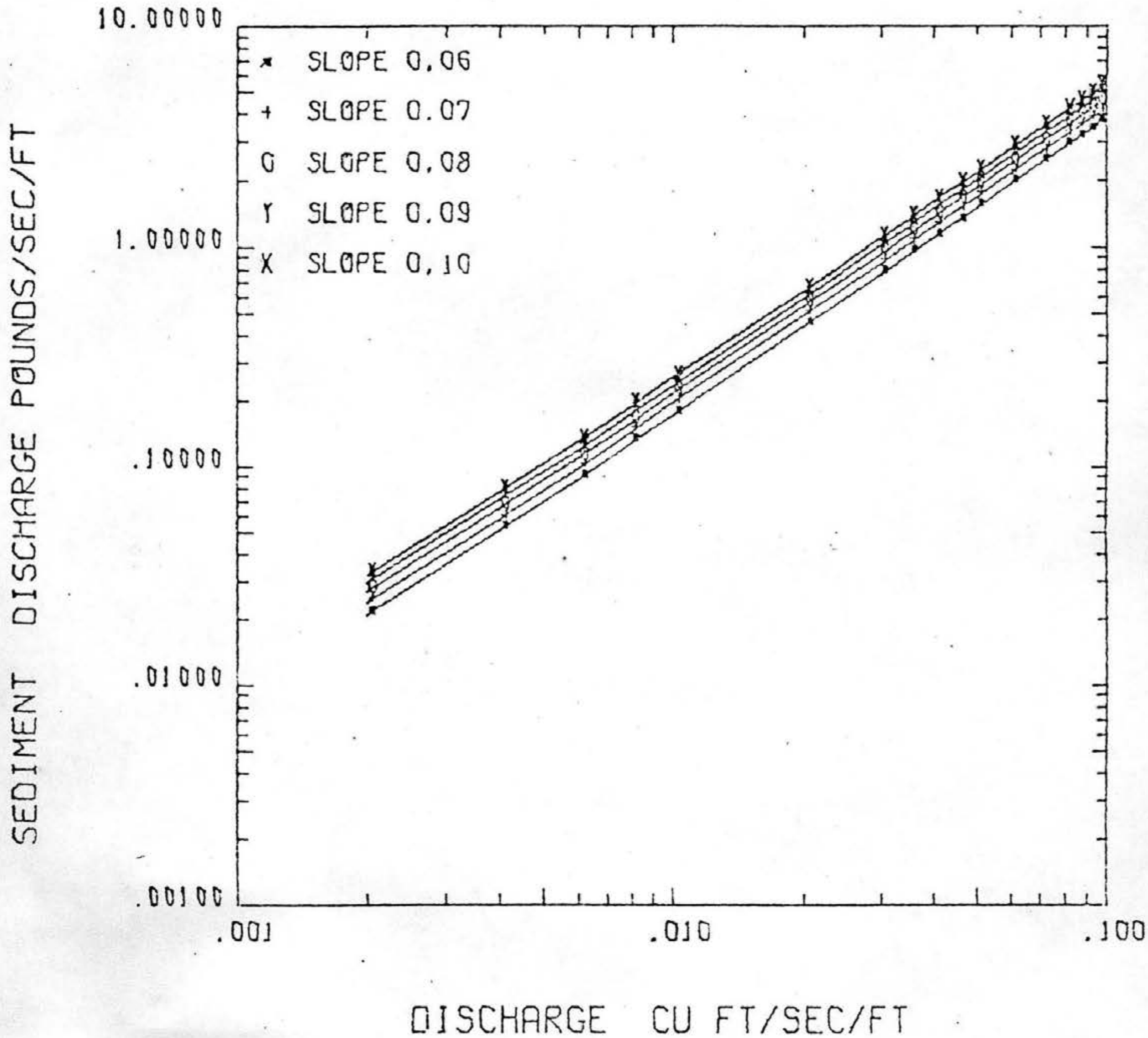

Fig. 31. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.06 to 0.10 and for Sediment Size of 0.02 mm

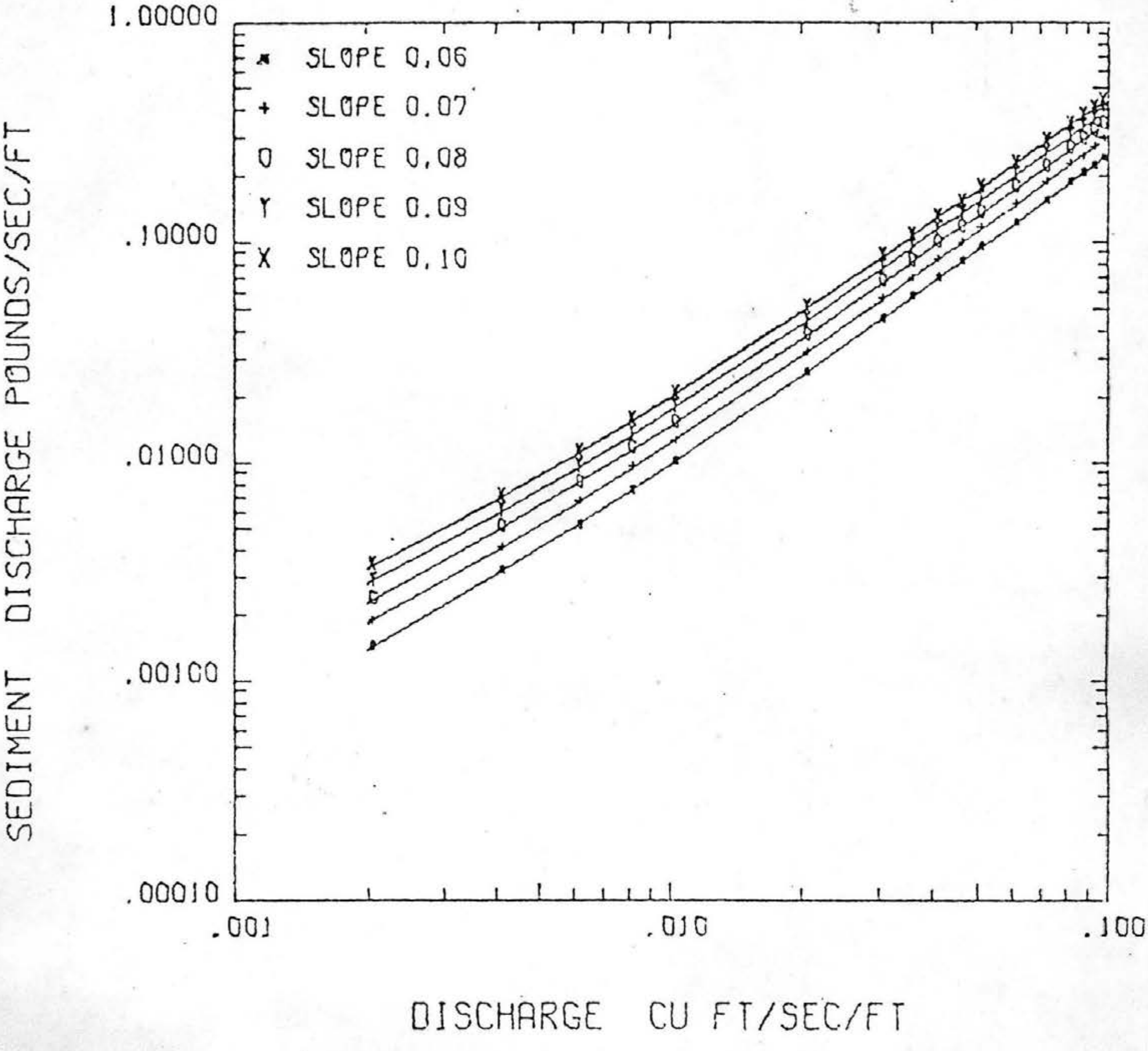

Fig. 32. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.06 to 0.10 and for Sediment Size of 0.1 mm

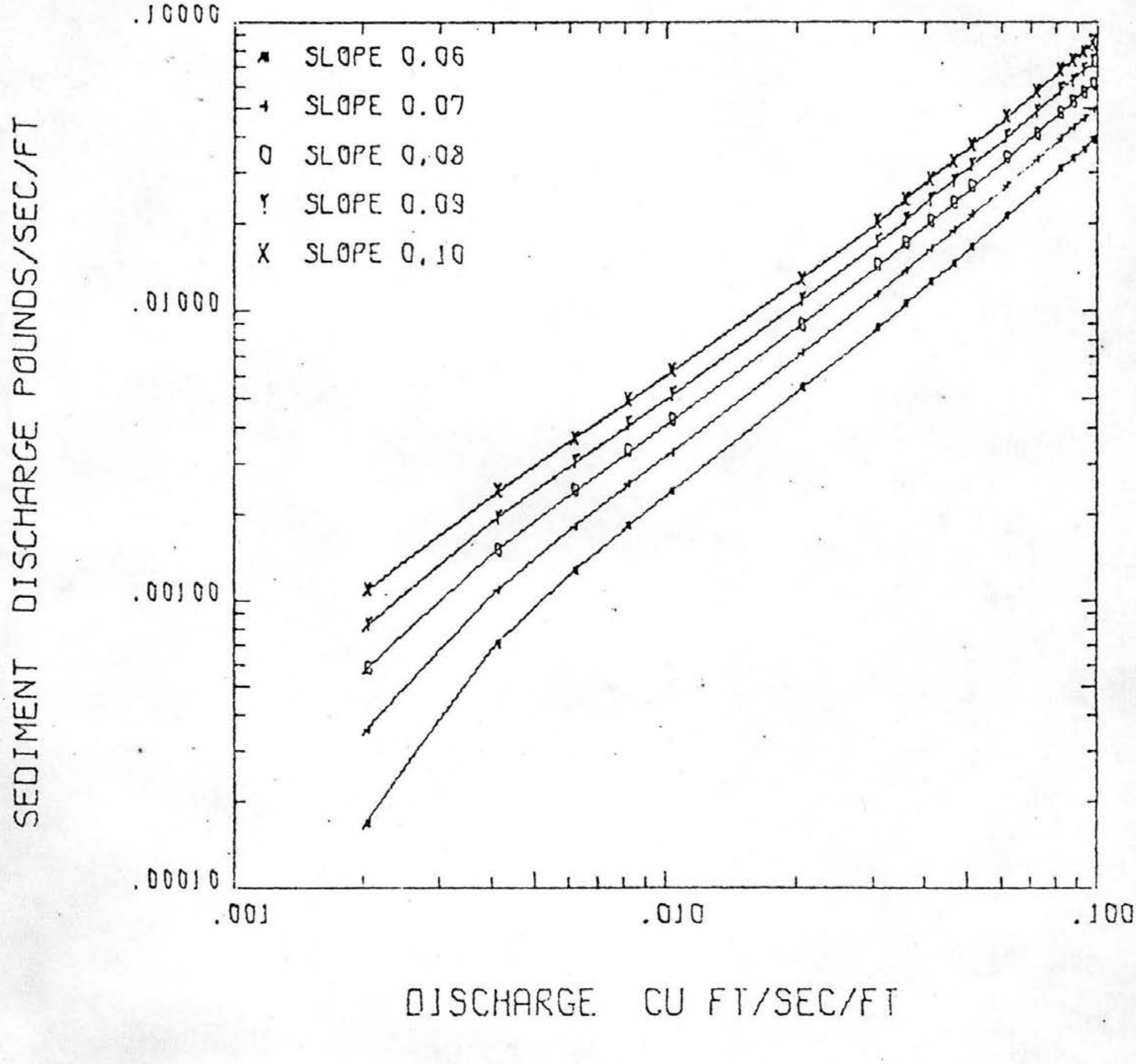

Fig. 33. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.06 to 0.10 and for Sediment Size of 0.2 mm

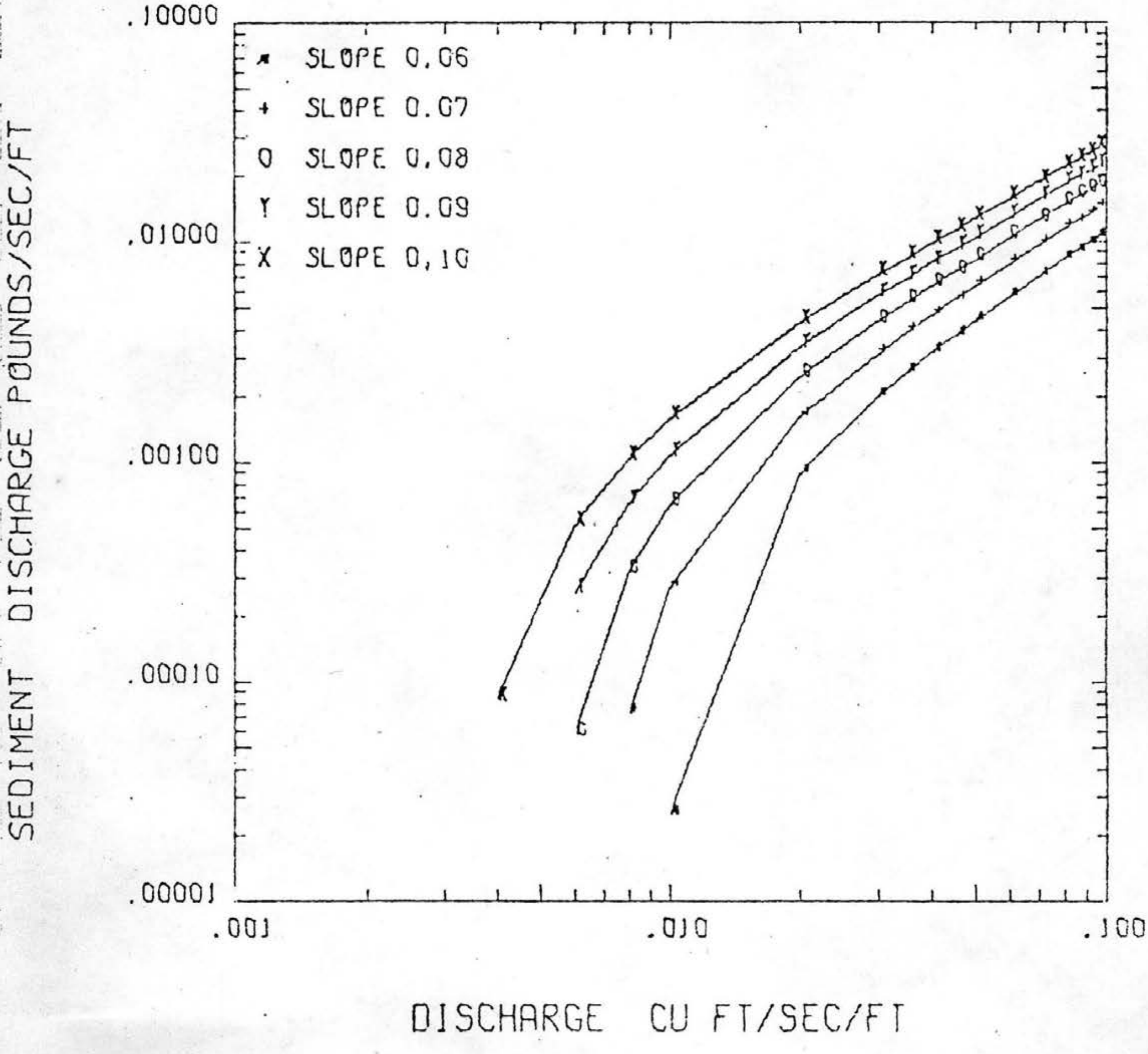

Fig. 34. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.06 to 0.10 and for Sediment Size of 0.4 mm

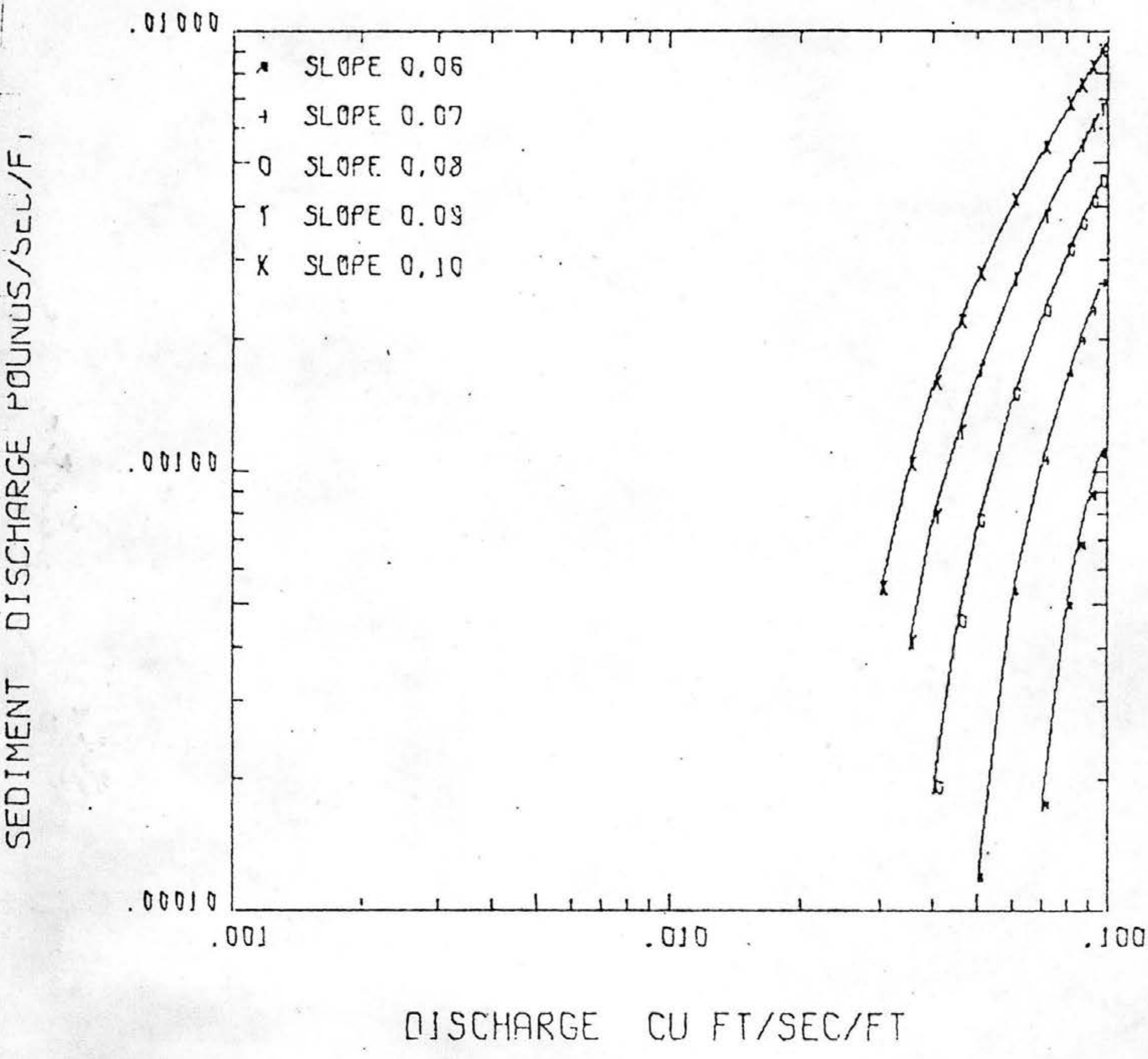

Fig. 35. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.06 to 0.10 and for Sediment Size of 0.75 mm

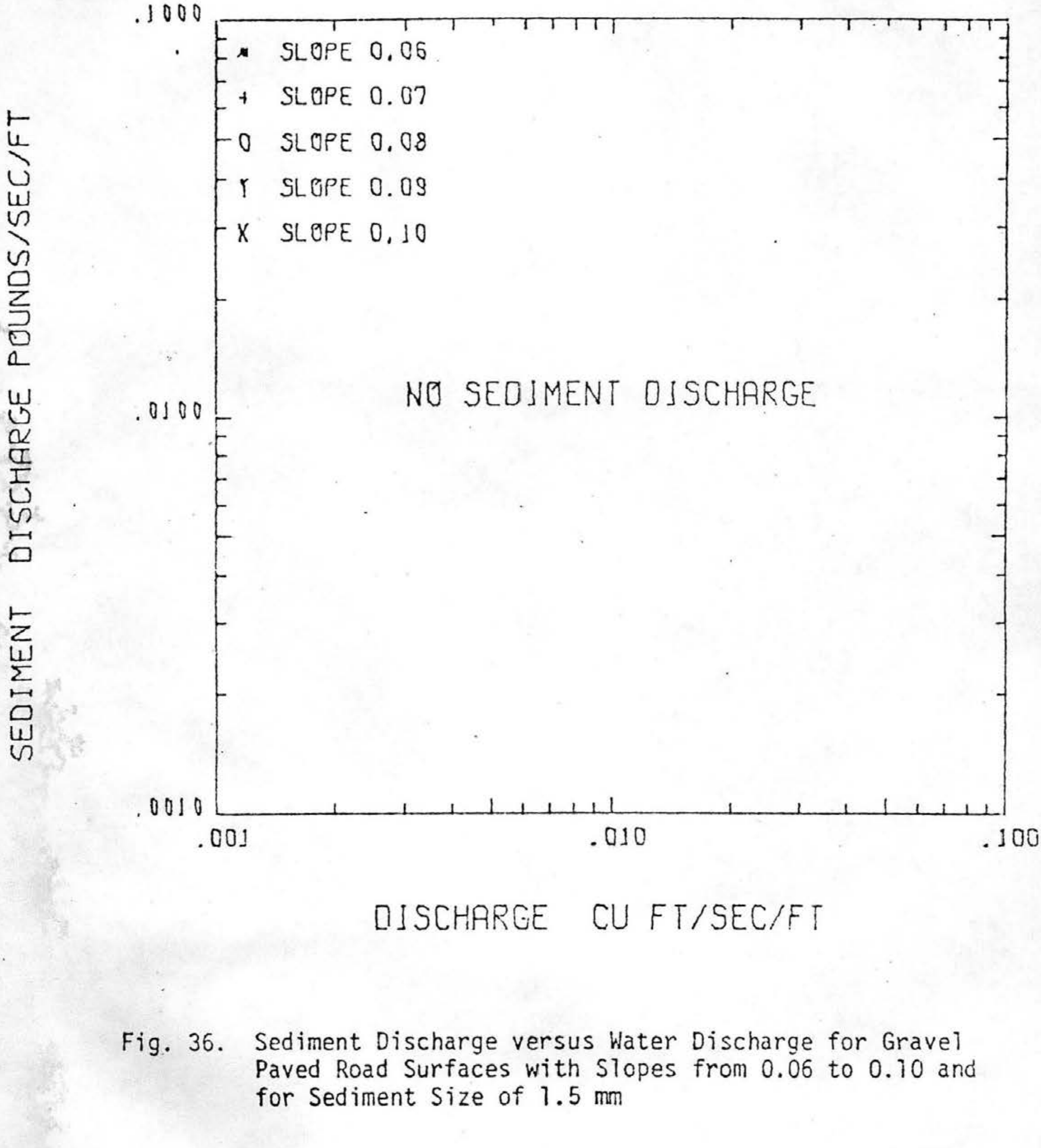

Fig. 36. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.06 to 0.10 and for Sediment Size of 1.5 mm

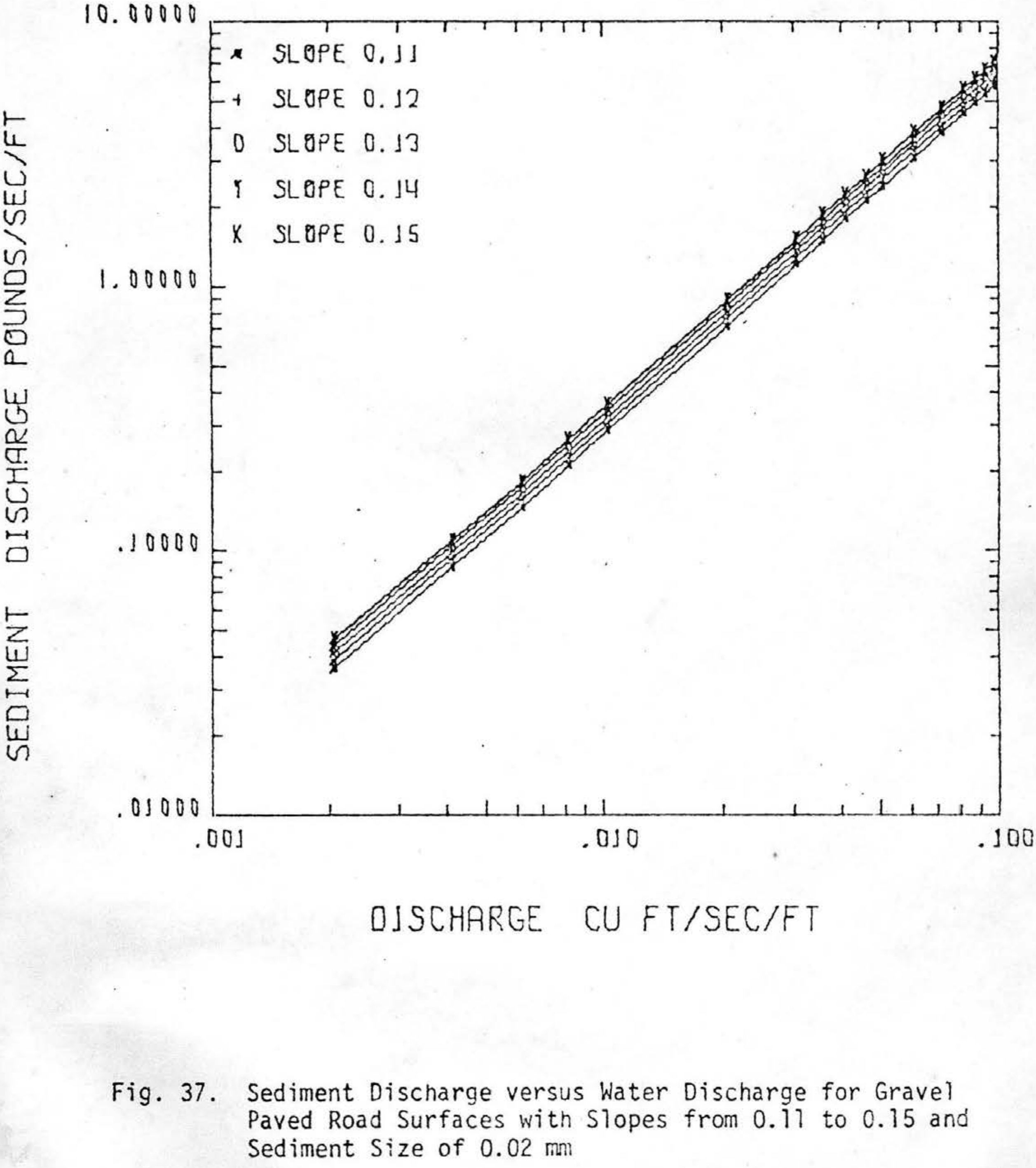

Fig. 37. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.11 to 0.15 and Sediment Size of 0.02 mm

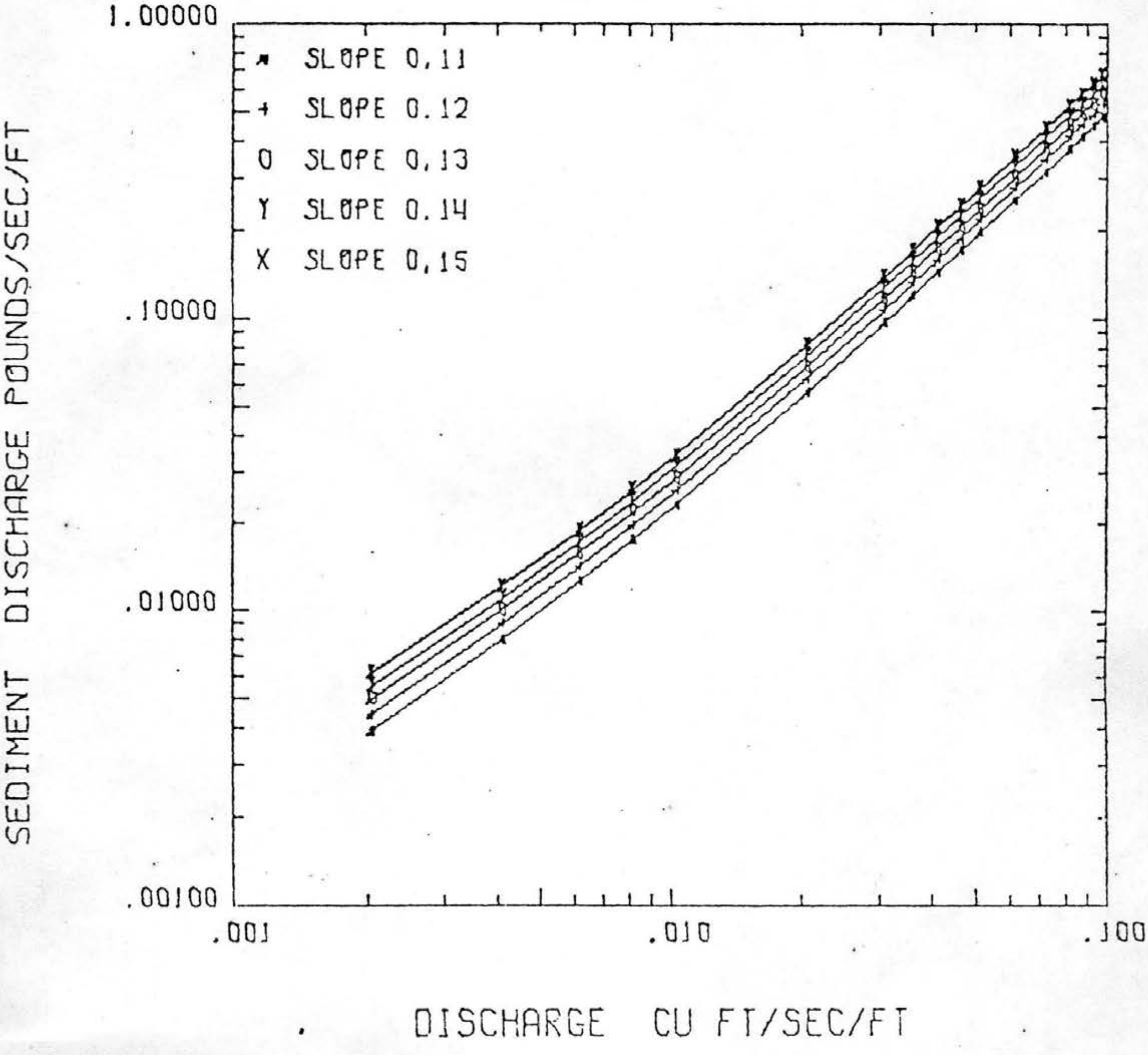

Fig. 38. Sediment Discharge versus Discharge for Gravel Paved Road Surfaces with Slopes from 0.11 to 0.15 and Sediment Size of 0.1 mm

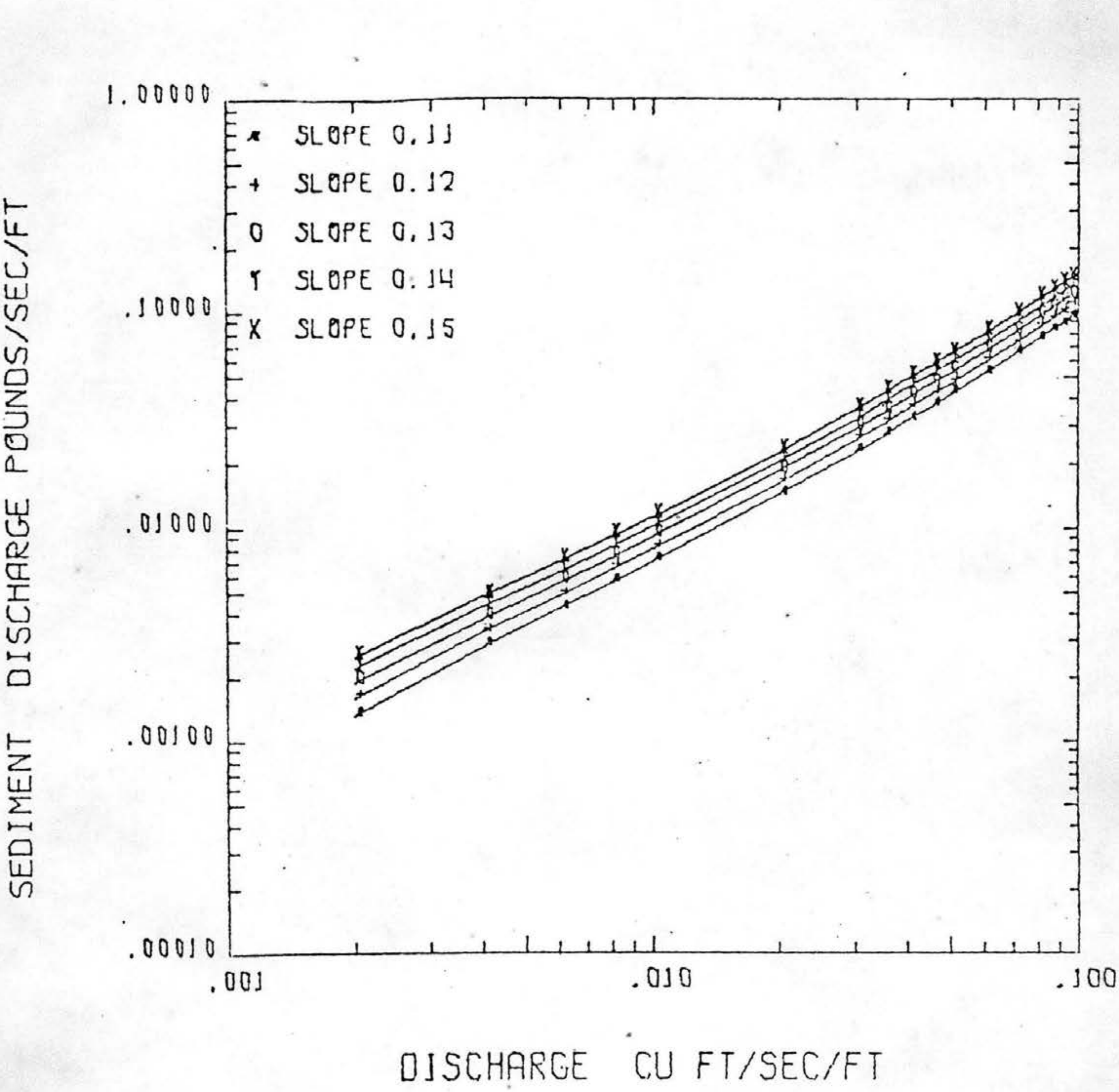

Fig. 39. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.11 to 0.15 and Sediment Size of 0.2 mm

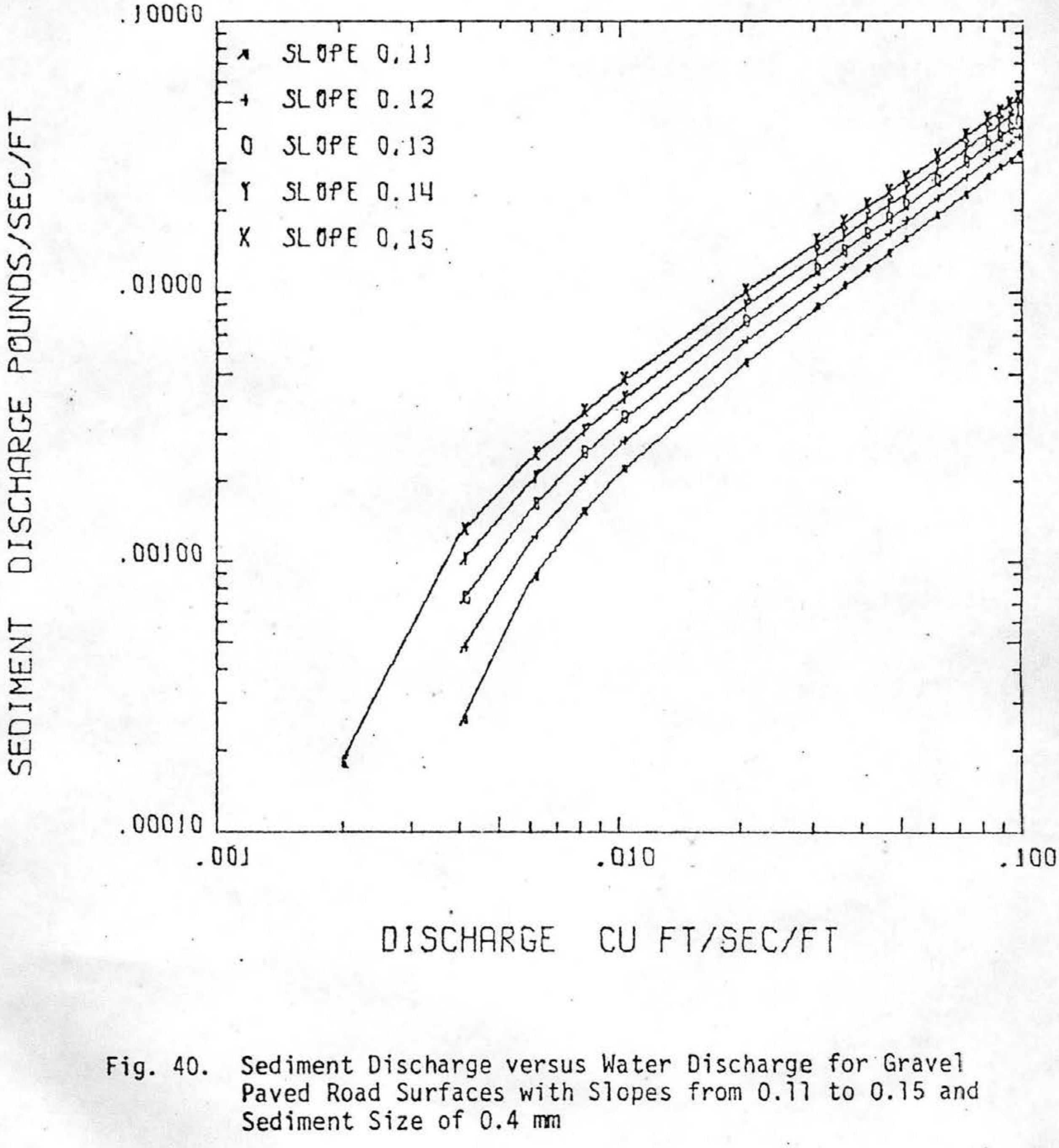

Fig. 40. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.11 to 0.15 and Sediment Size of 0.4 mm

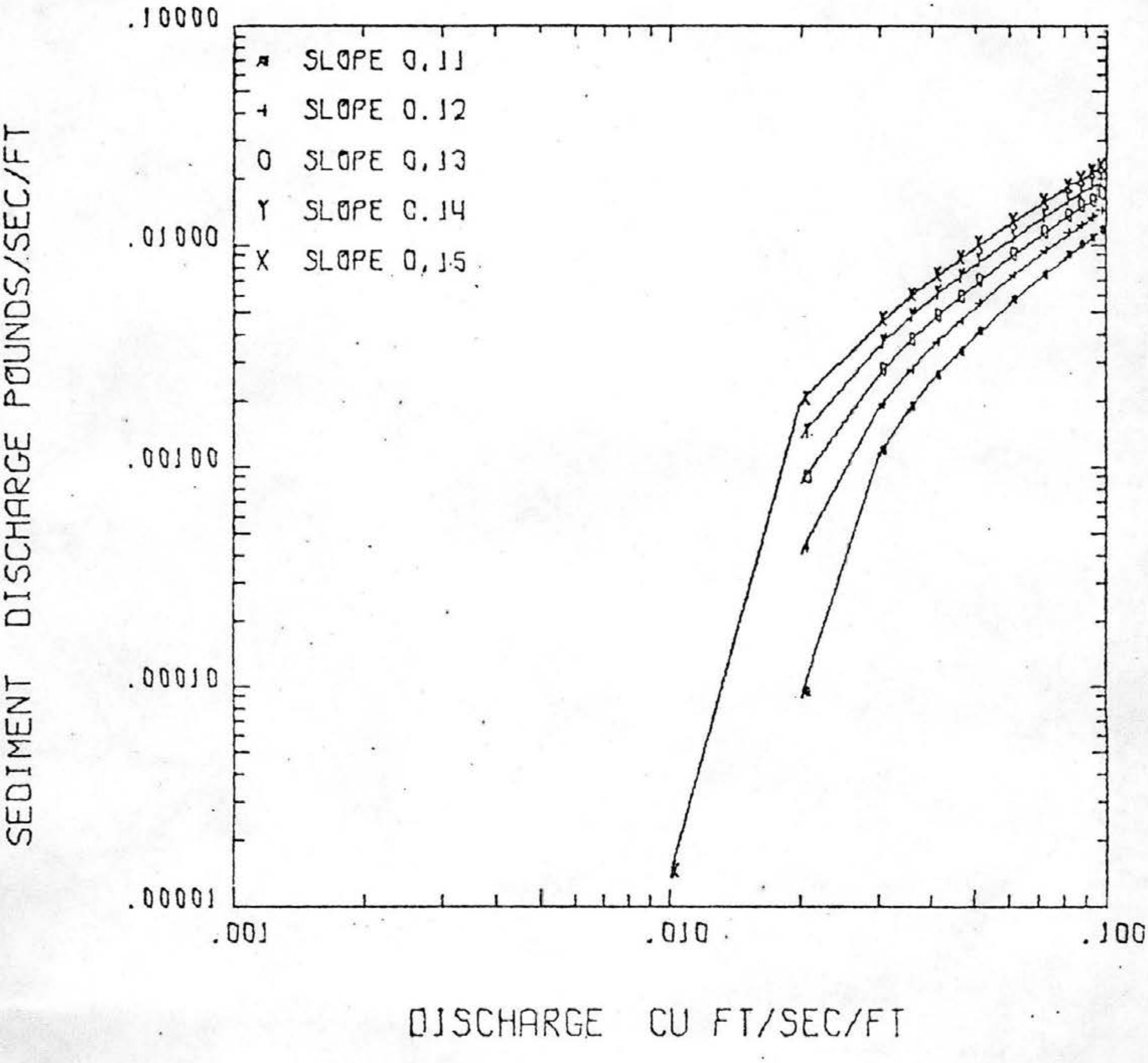

Fig. 41. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.11 to 0.15 and Sediment Size of 0.75 mm

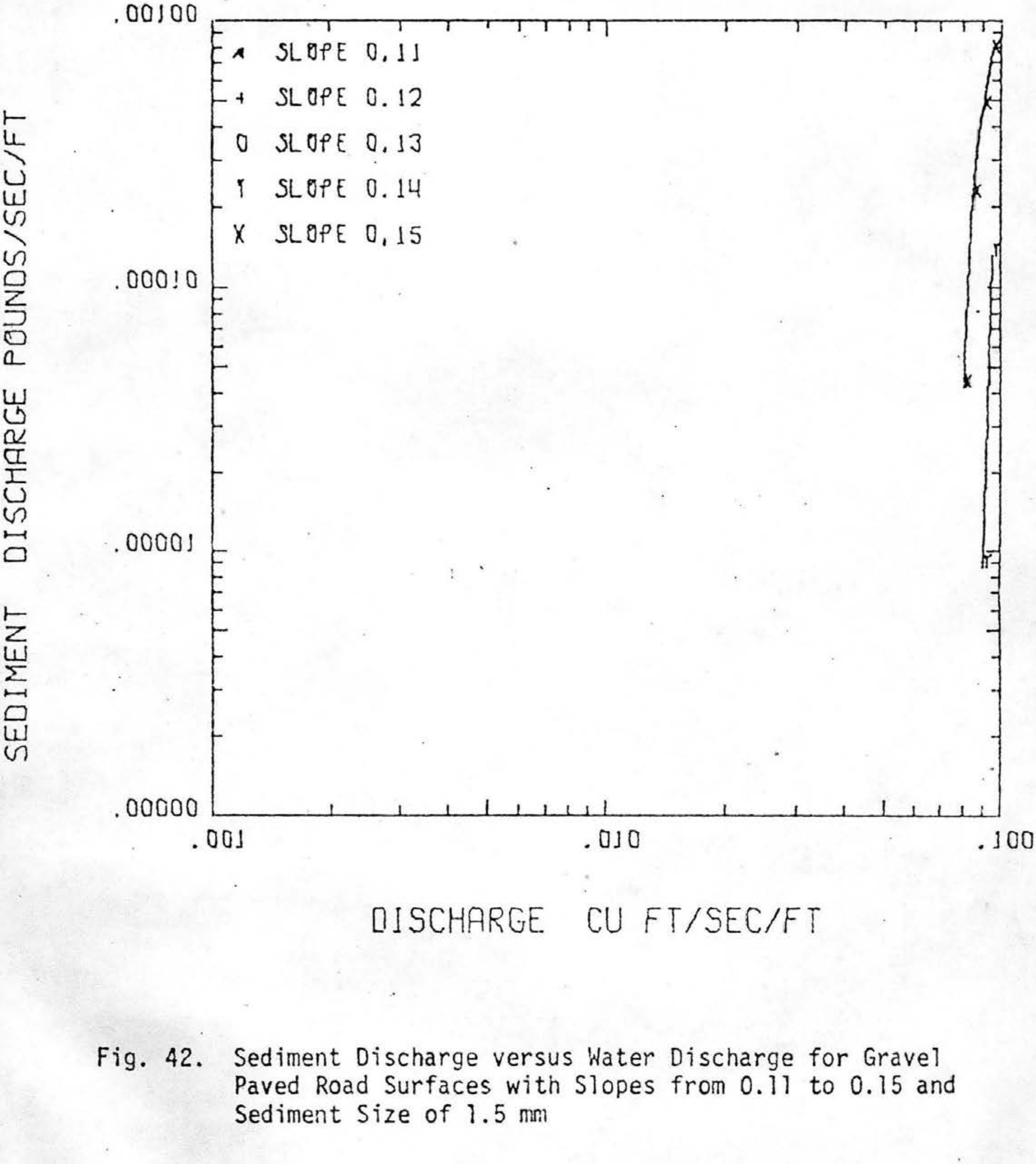

Fig. 42. Sediment Discharge versus Water Discharge for Gravel Paved Road Surfaces with Slopes from 0.11 to 0.15 and Sediment Size of 1.5 mm

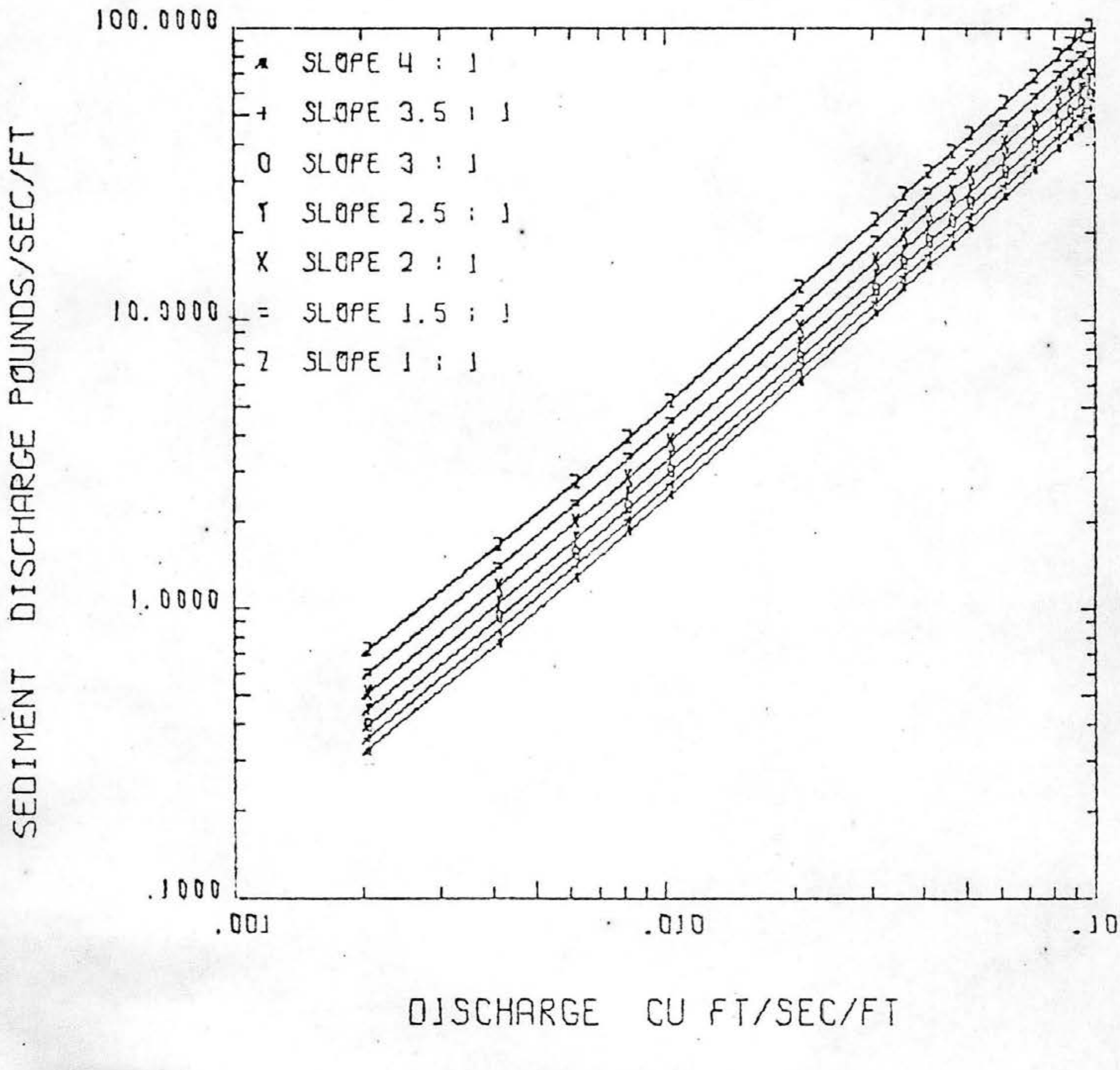

Fig. 43. Sediment Discharge versus Water Discharge for Bare-Soil Cut and Fill Slopes and for Sediment Size of 0.02 mm

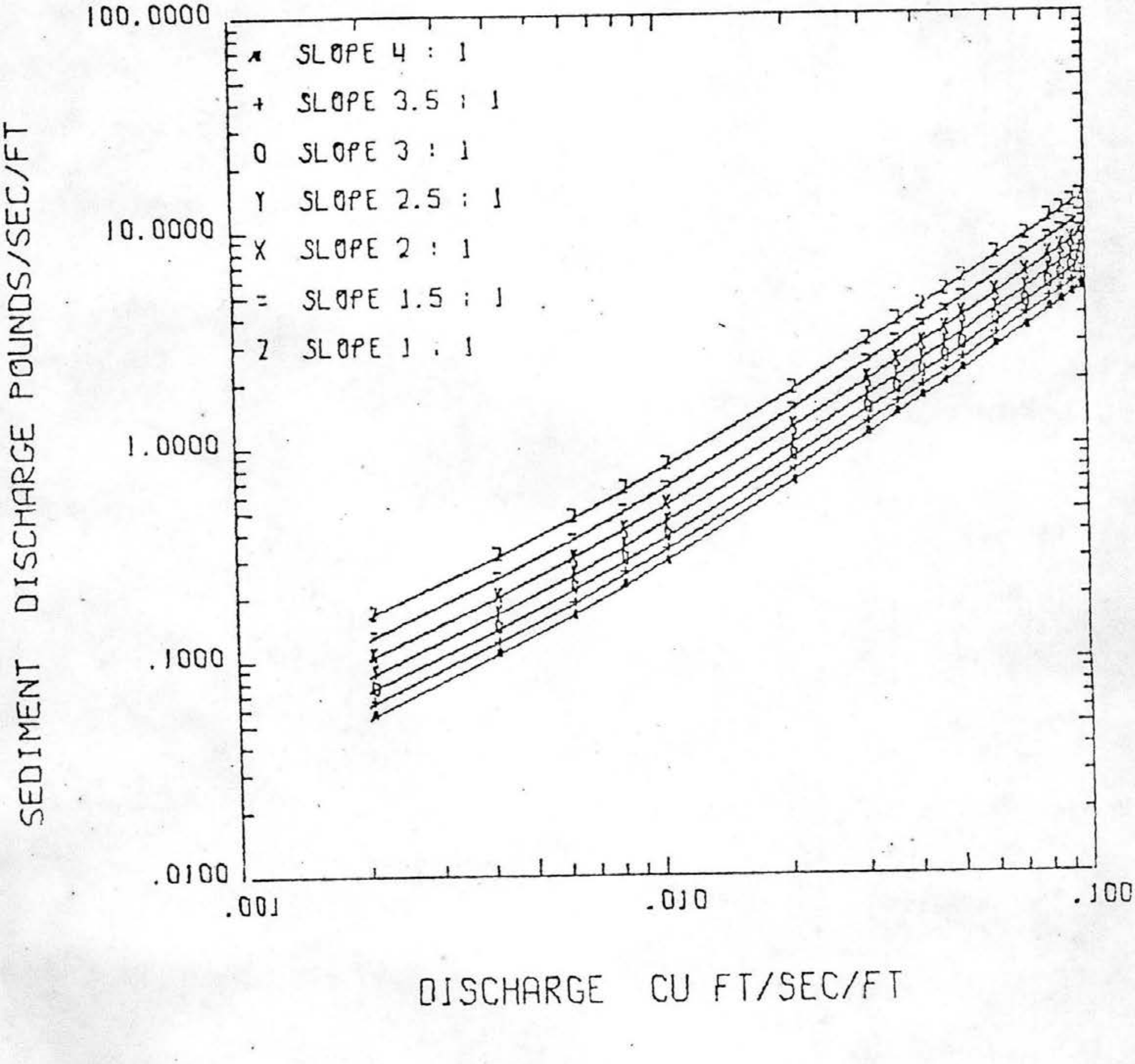

Fig. 44. Sediment Discharge versus Water Discharge for Bare-Soil Cut and Fill Slopes and for Sediment Size of 0.1 mm

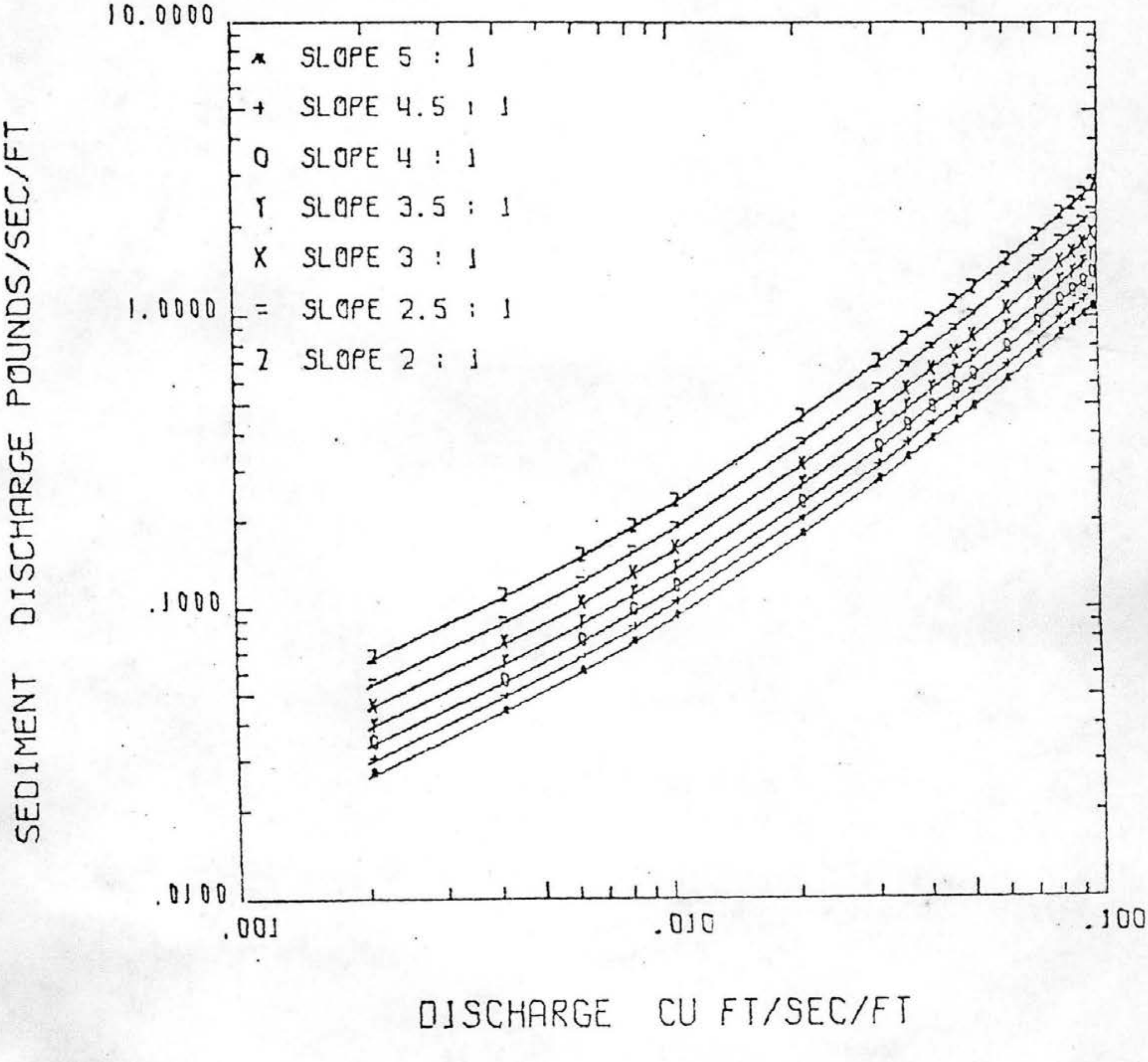

Fig. 45. Sediment Discharge versus Water Discharge for Bare-Soil Cut and Fill Slopes and for Sediment Size of 0.2 mm

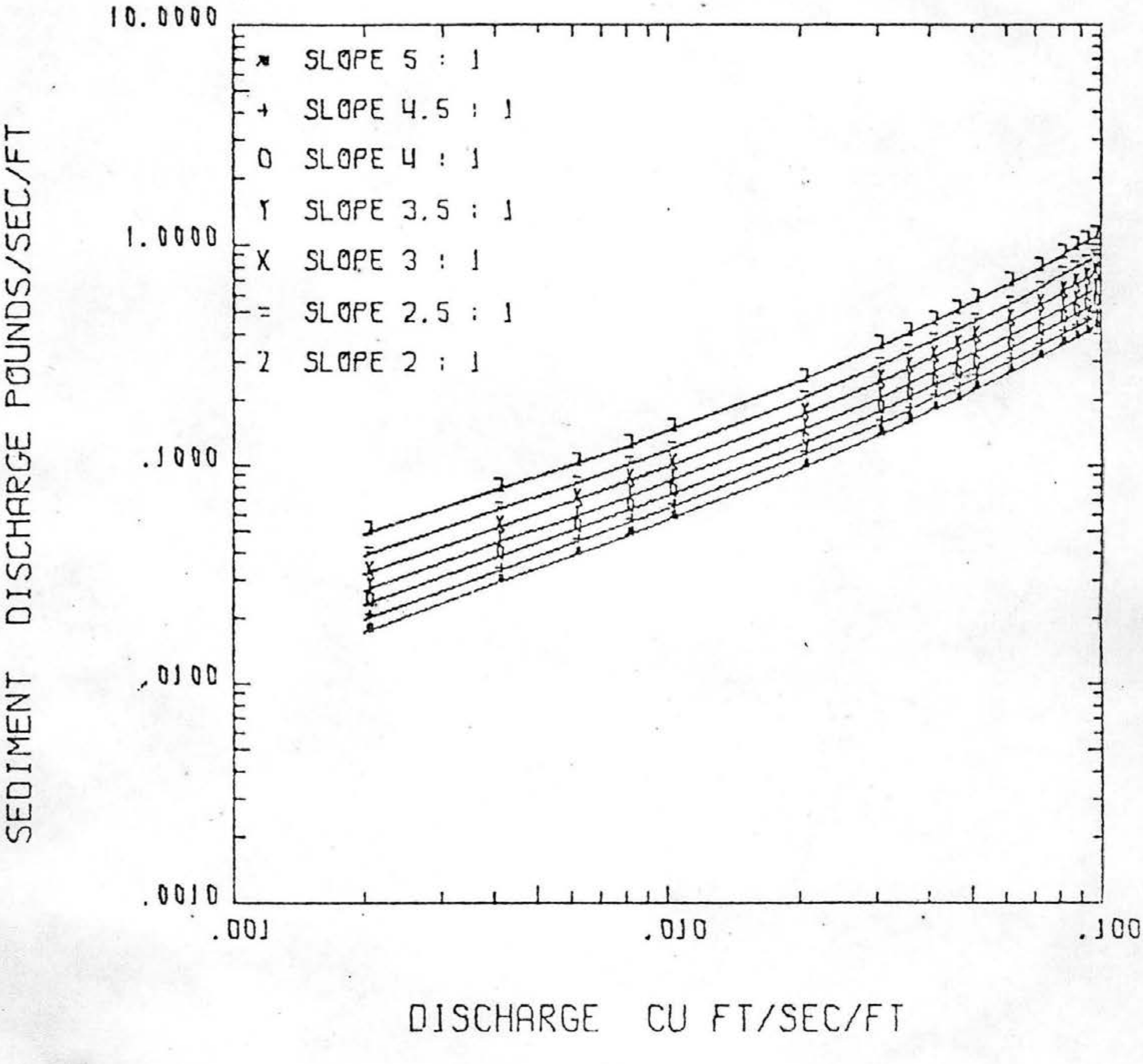

Fig. 46. Sediment Discharge versus Water Discharge for Bare-Soil Cut and Fill Slopes and for Sediment Size of 0.4 mm

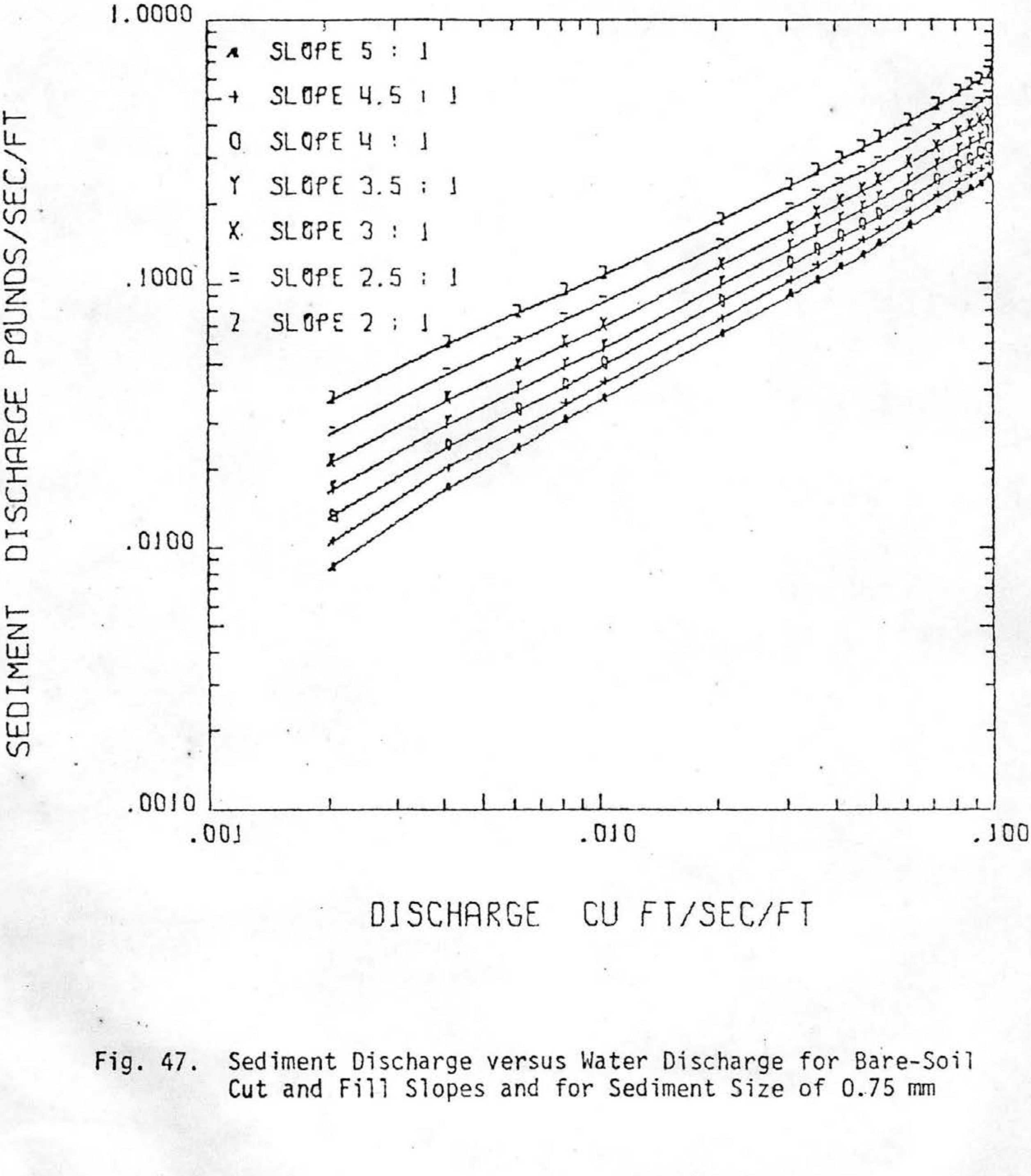

Fig. 47. Sediment Discharge versus Water Discharge for Bare-Soil Cut and Fill Slopes and for Sediment Size of 0.75 mm

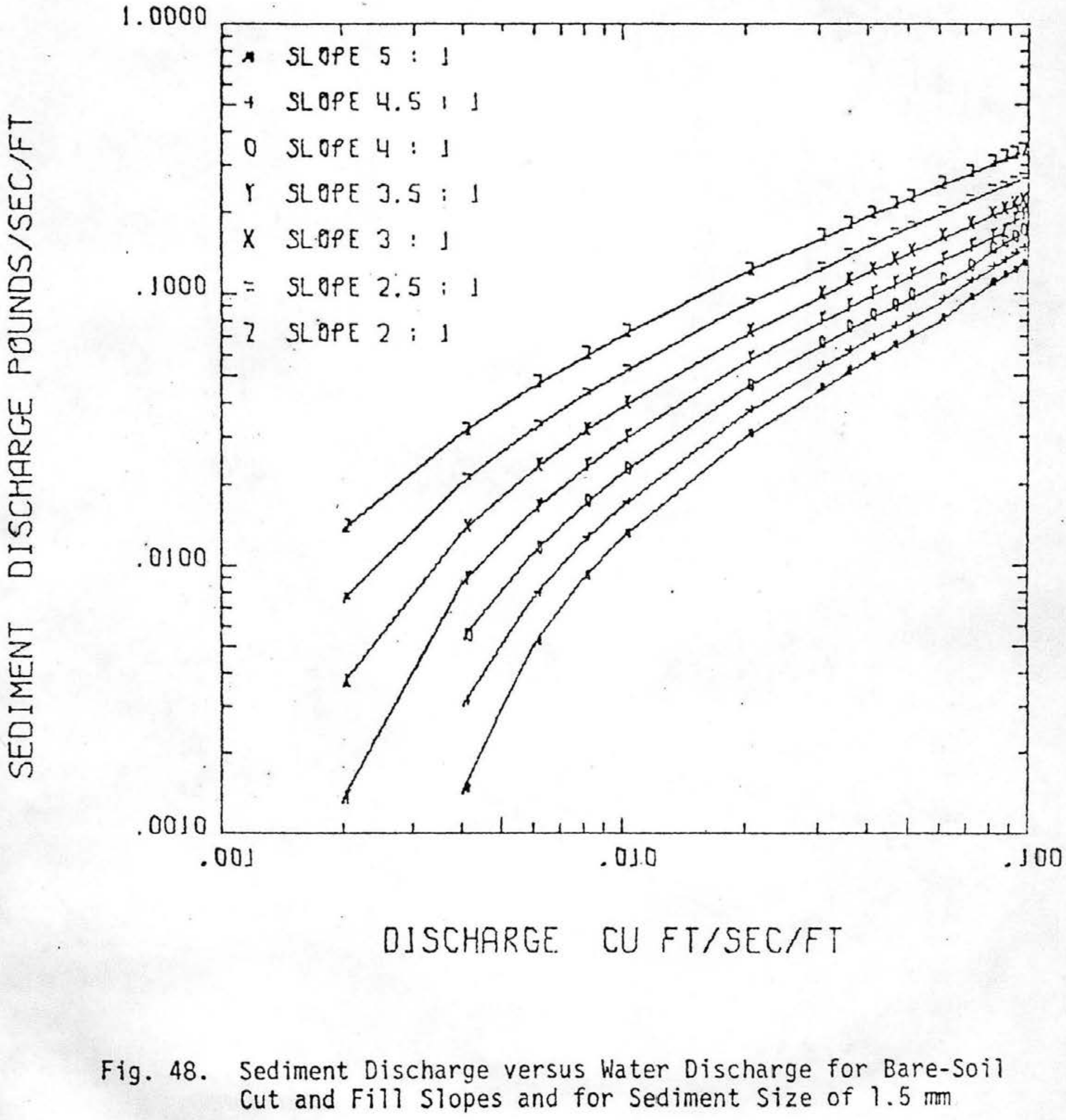

Fig. 48. Sediment Discharge versus Water Discharge for Bare-Soil Cut and Fill Slopes and for Sediment Size of 1.5 mm

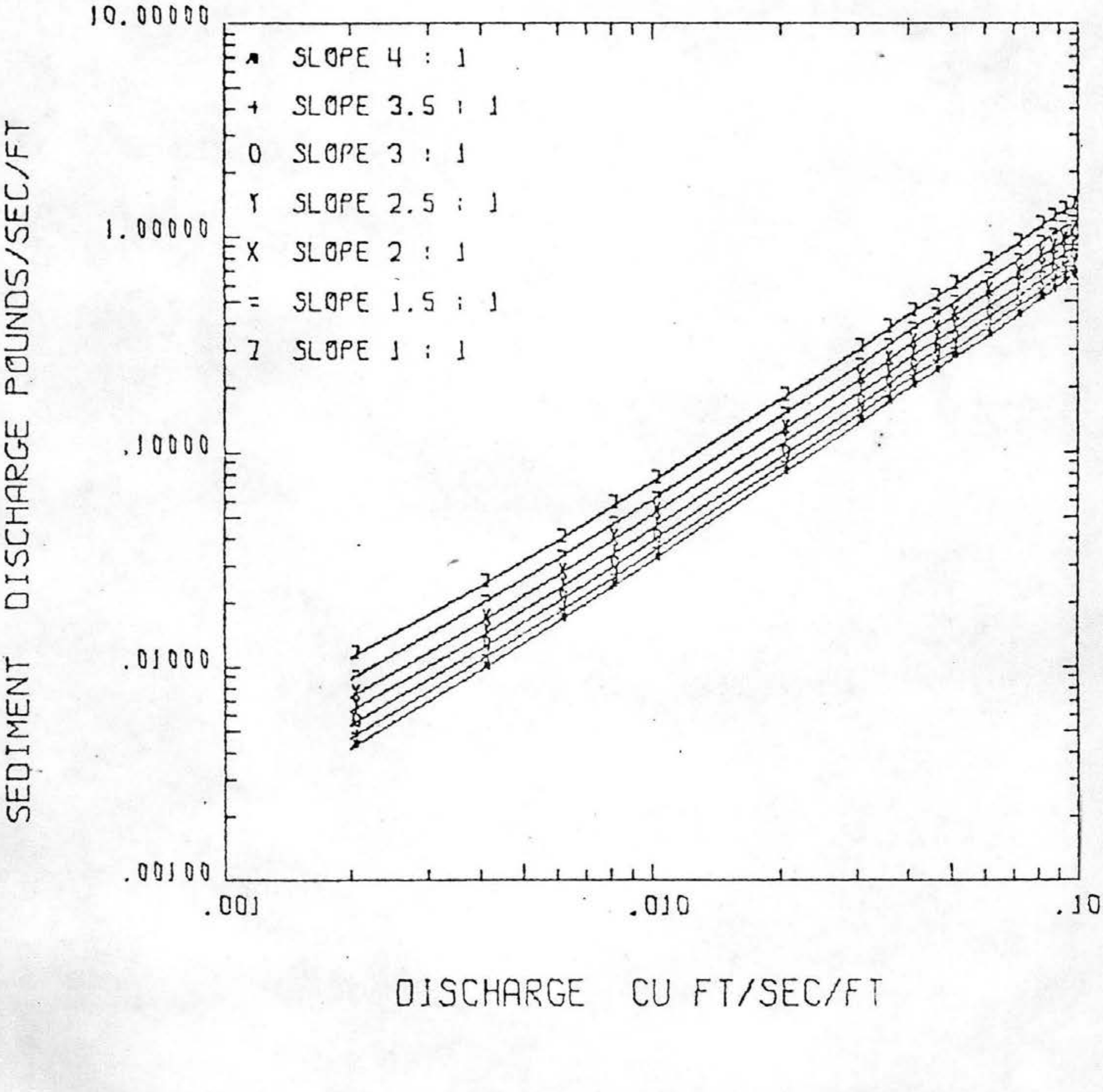

Fig. 49. Sediment Discharge versus Water Discharge for Sparse-Vegetation Cut and Fill Slopes and for Sediment Size of 0.02 mm

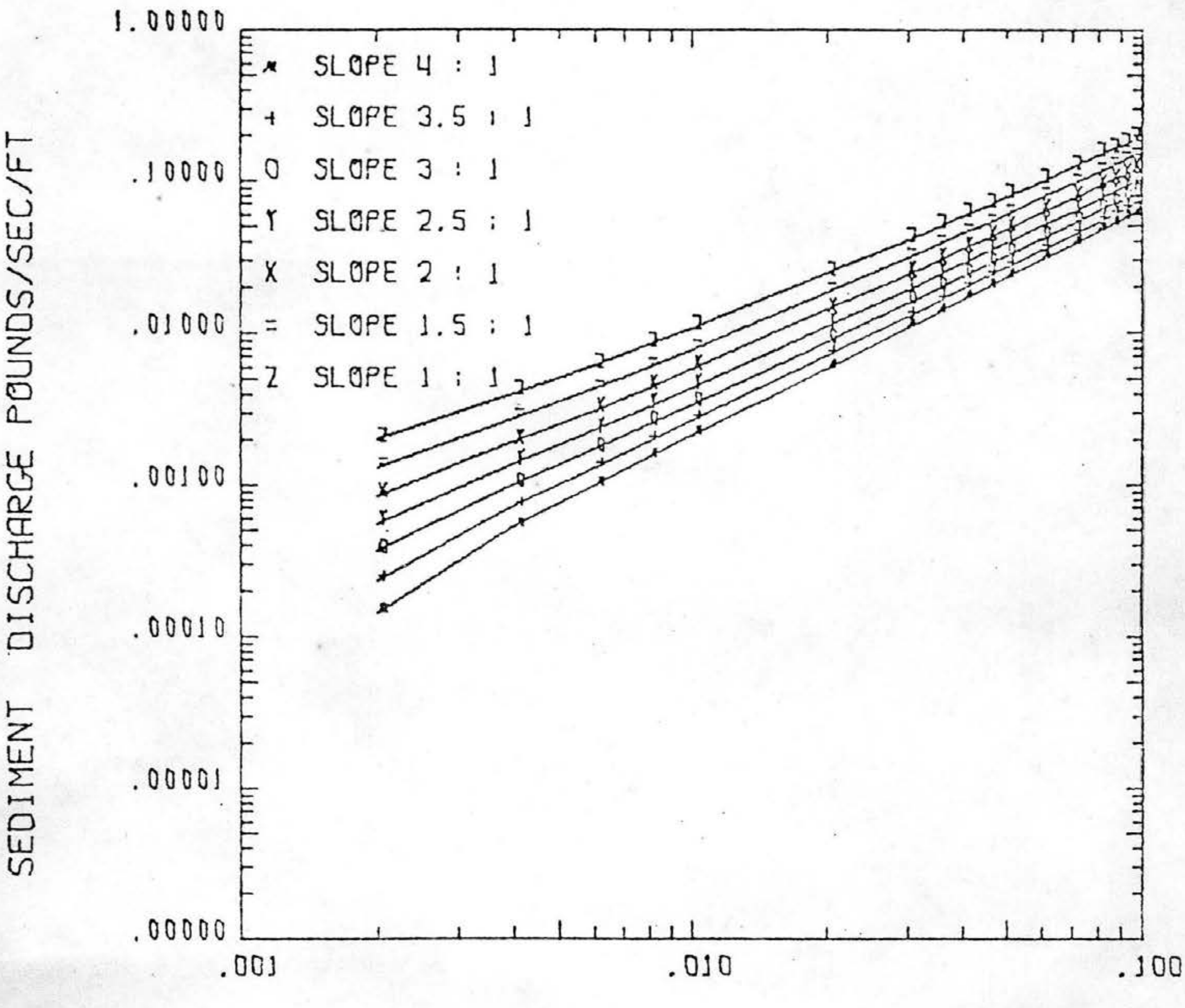

Fig. 50. Sediment Discharge versus Water Discharge for Sparse-Vegetation Cut and Fill Slopes and for Sediment Size of 0.1 mm

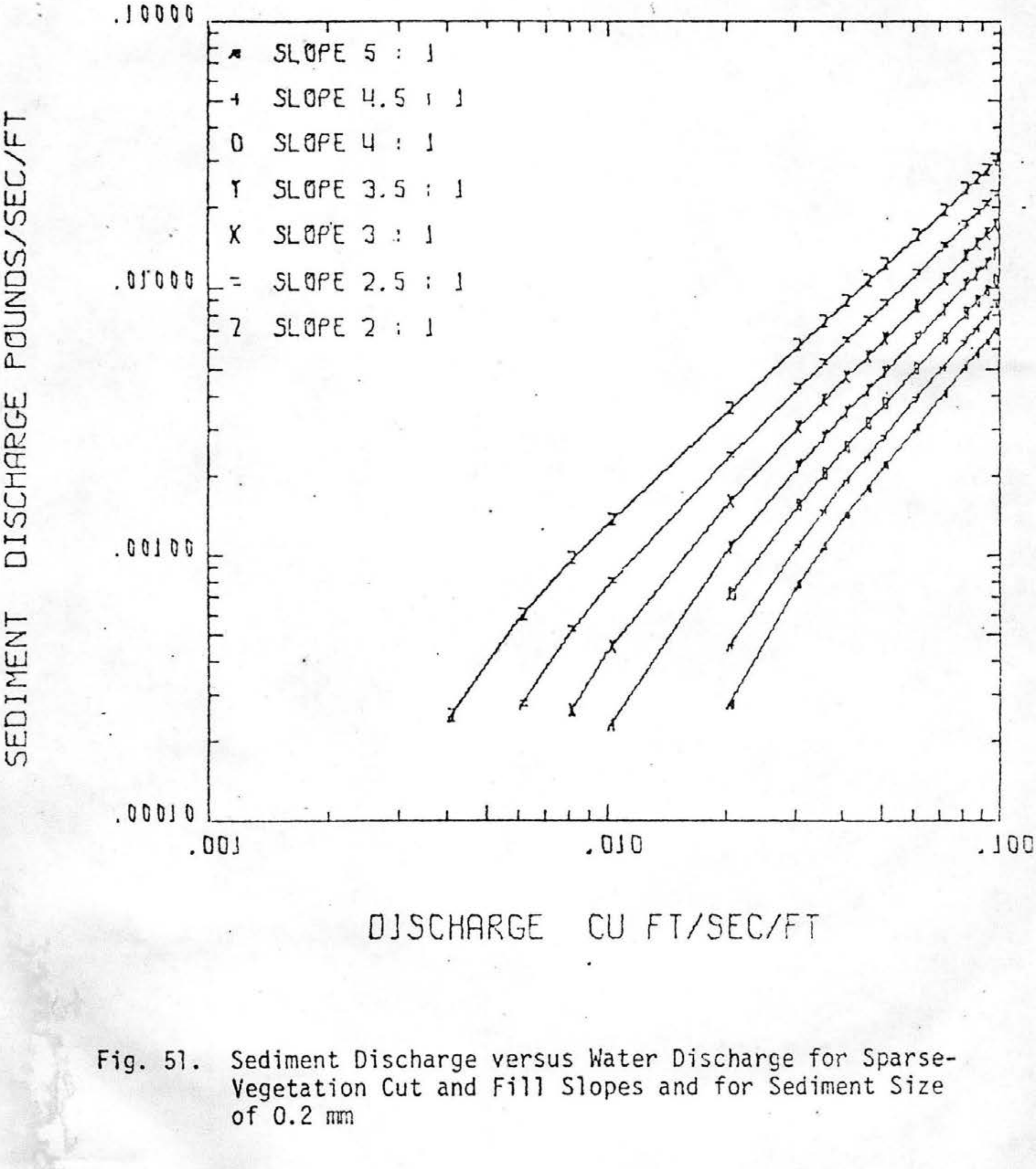

Fig. 51. Sediment Discharge versus Water Discharge for Sparse-Vegetation Cut and Fill Slopes and for Sediment Size of 0.2 mm

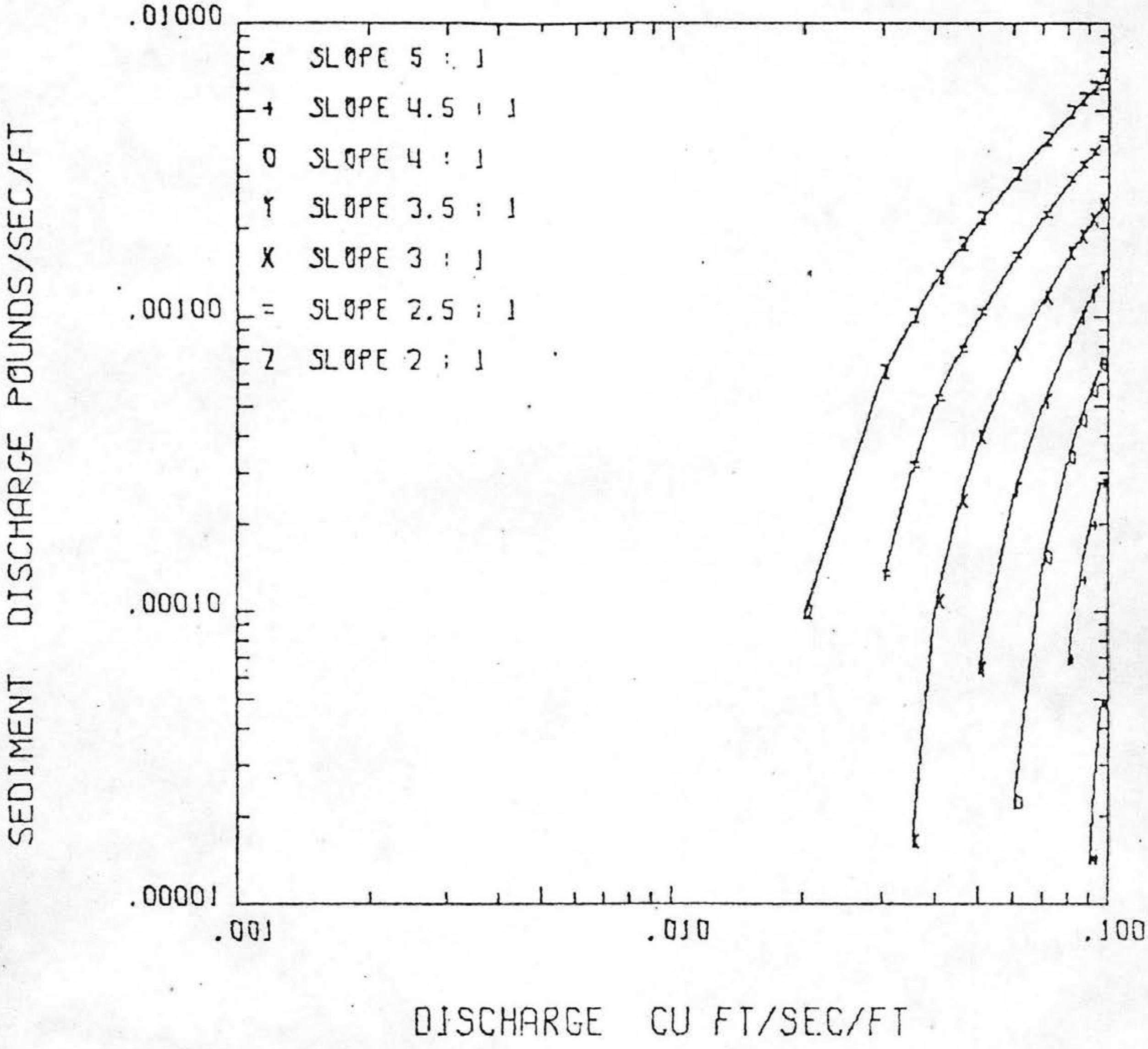

Fig. 52. Sediment Discharge versus Water Discharge for Sparse-Vegetation Cut and Fill Slopes and for Sediment Size of 0.4 mm

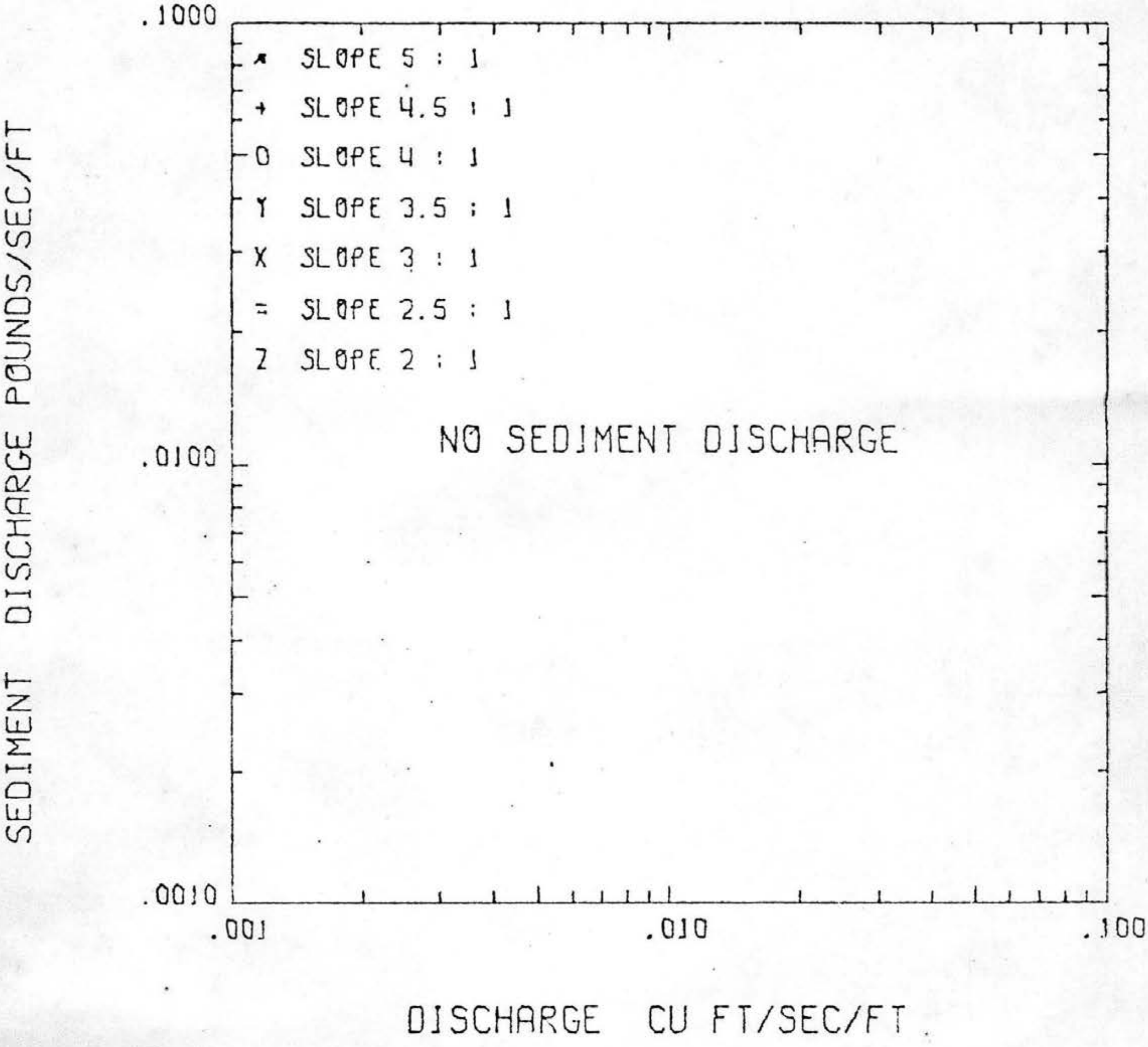

Fig. 53. Sediment Discharge versus Water Discharge for Sparse-Vegetation Cut and Fill Slopes and for Sediment Size of 0.75 mm

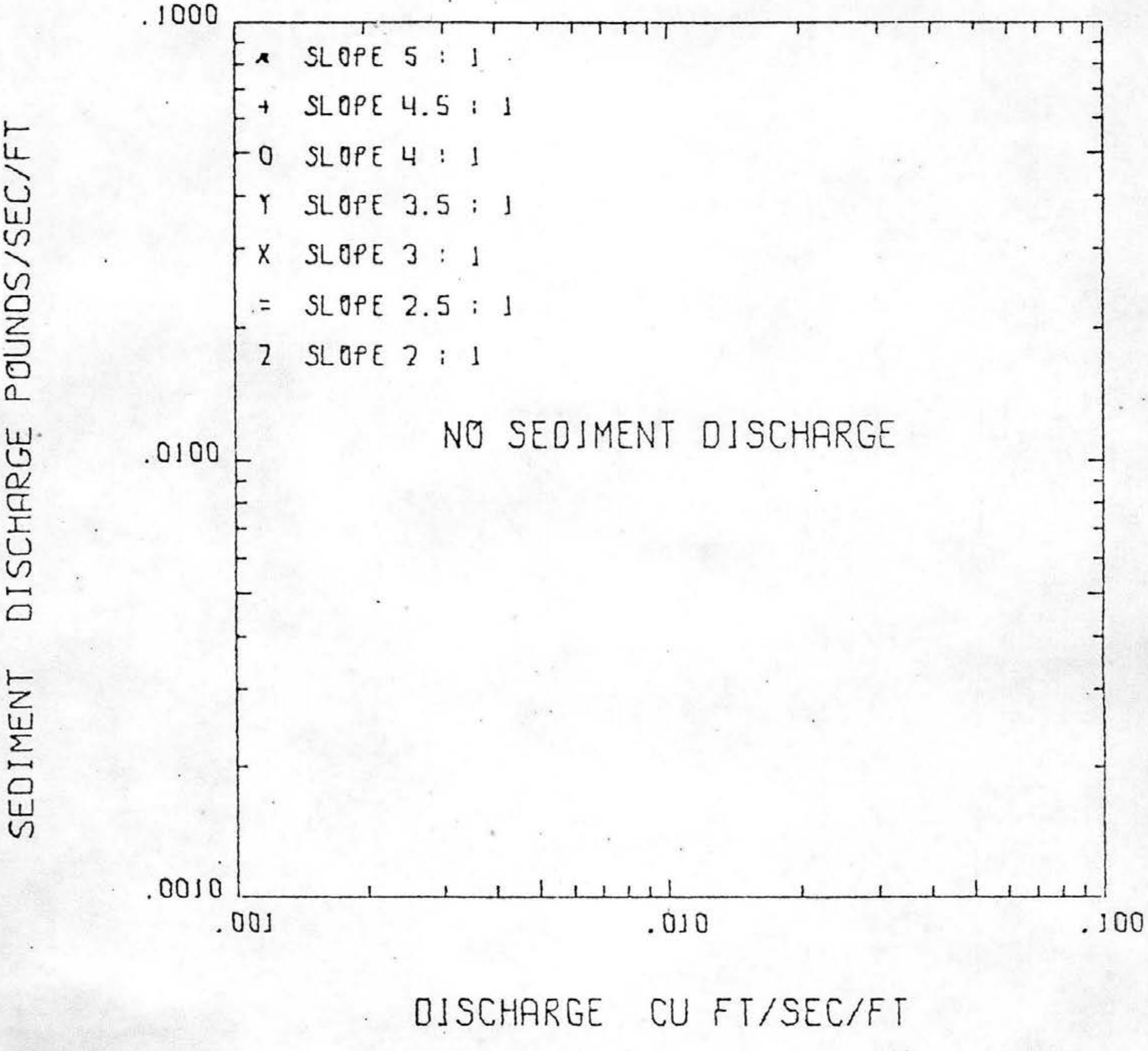

Fig. 54. Sediment Discharge versus Water Discharge for Sparse-Vegetation Cut and Fill Slopes and for Sediment Size of 1.5 mm

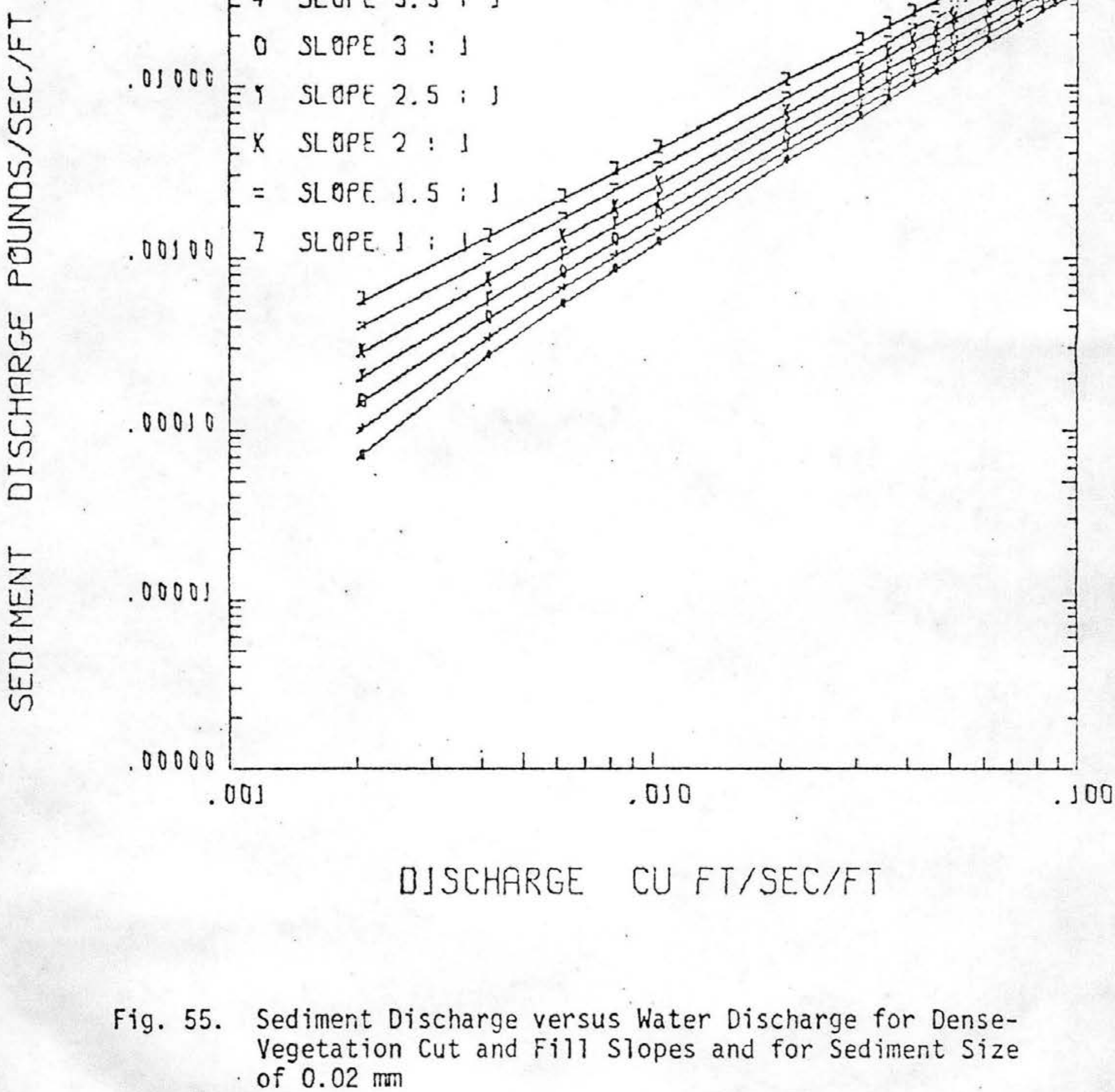

Fig. 55. Sediment Discharge versus Water Discharge for Dense-Vegetation Cut and Fill Slopes and for Sediment Size of 0.02 mm

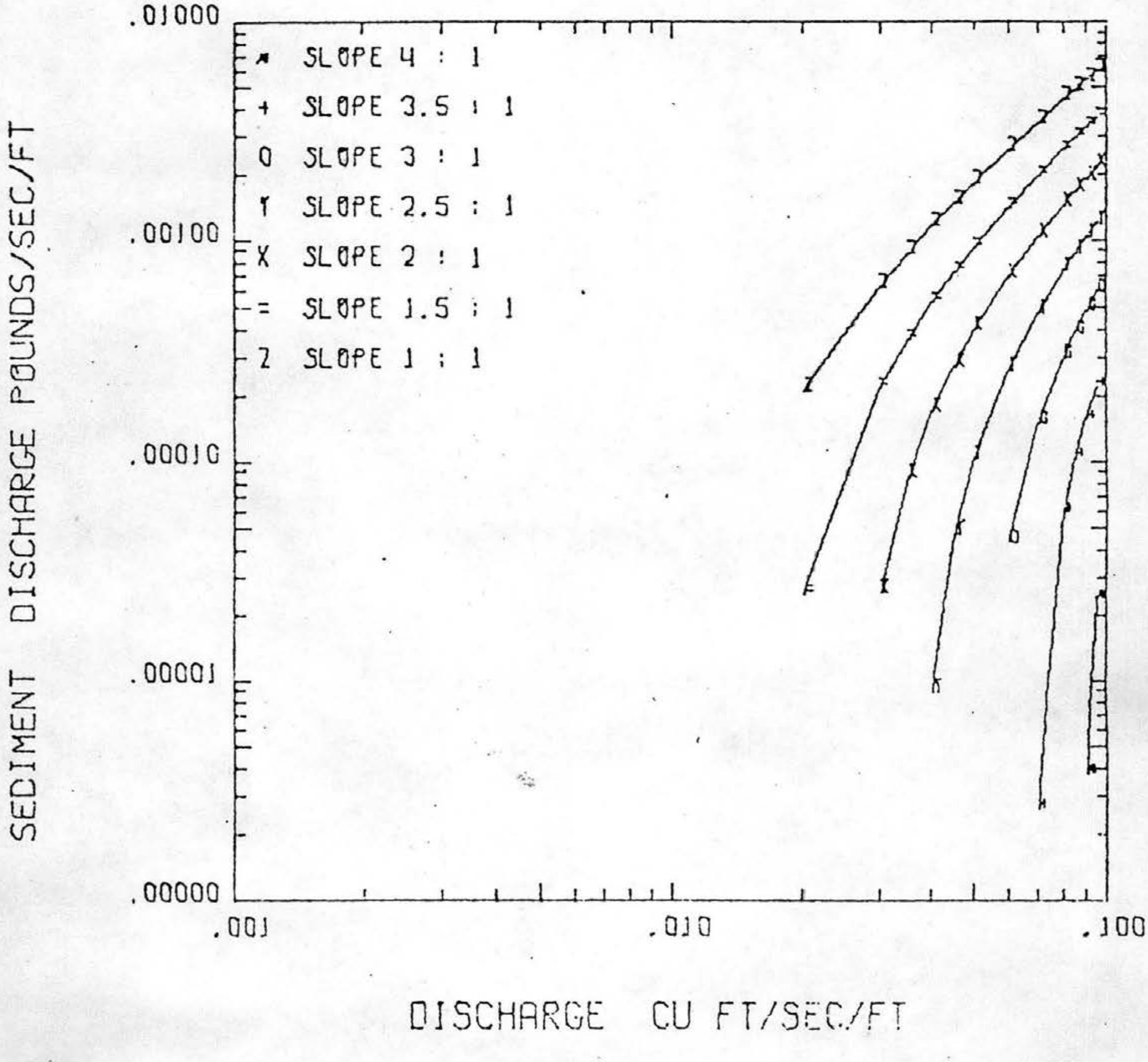

Fig. 56. Sediment Discharge versus Water Discharge for Dense-Vegetation Cut and Fill Slopes and for Sediment Size of 0.1 mm

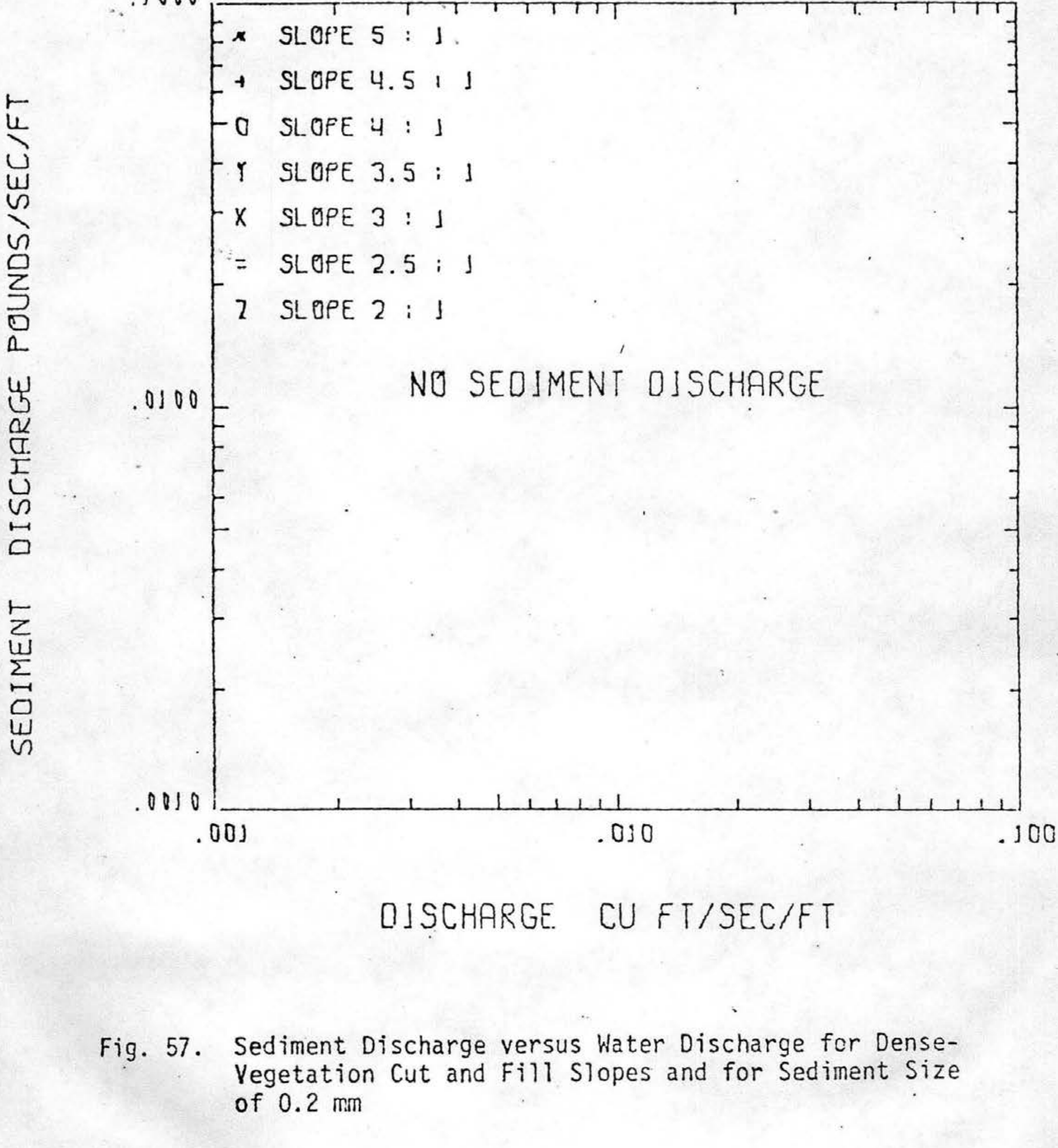

Fig. 57. Sediment Discharge versus Water Discharge for Dense-Vegetation Cut and Fill Slopes and for Sediment Size of 0.2 mm

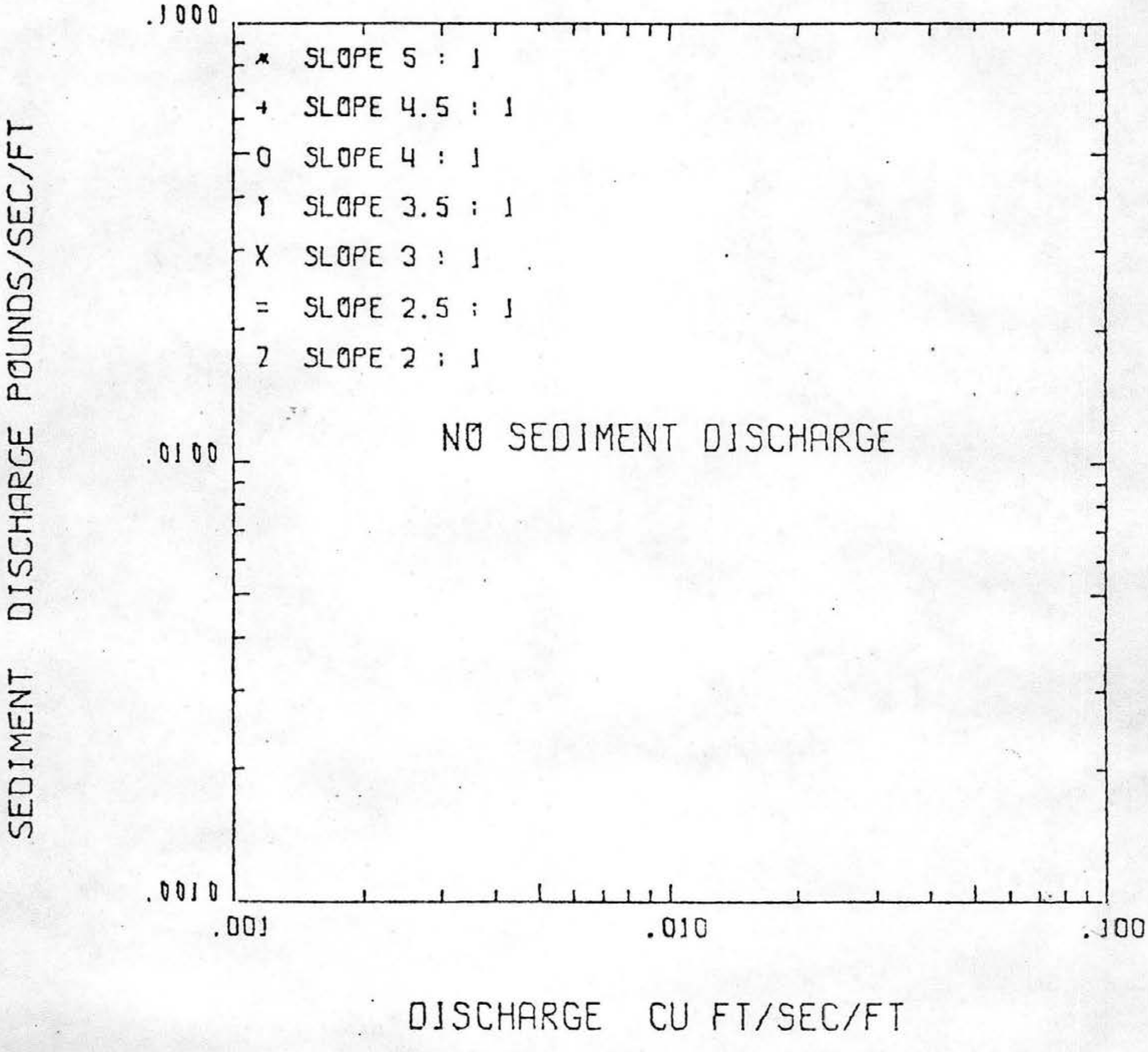

Fig. 58. Sediment Discharge versus Water Discharge for Dense-Vegetation Cut and Fill Slopes and for Sediment Size of 0.4 mm

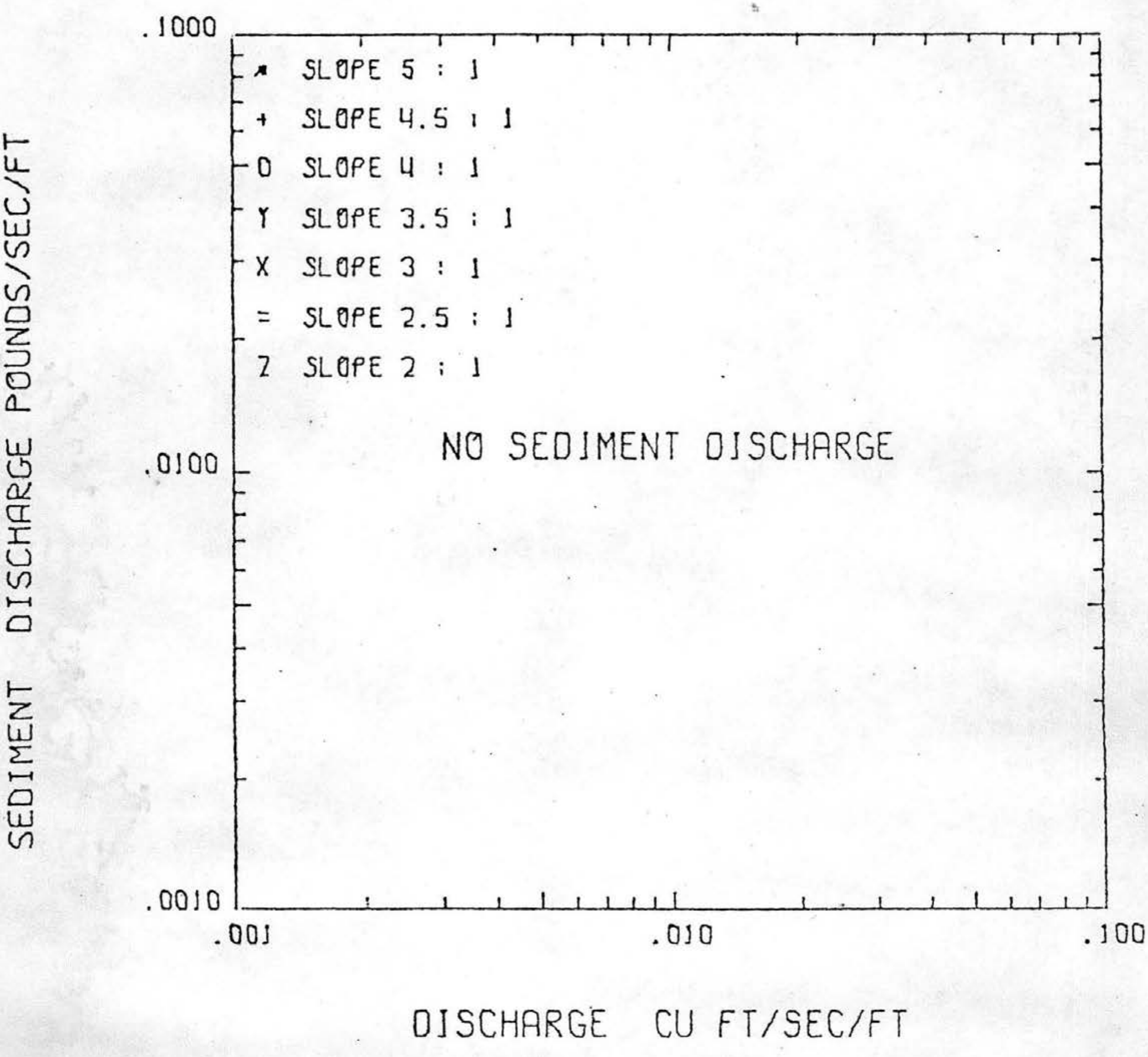

Fig. 59. Sediment Discharge versus Water Discharge for Dense-Vegetation Cut and Fill Slopes and for Sediment Size of 0.75 mm

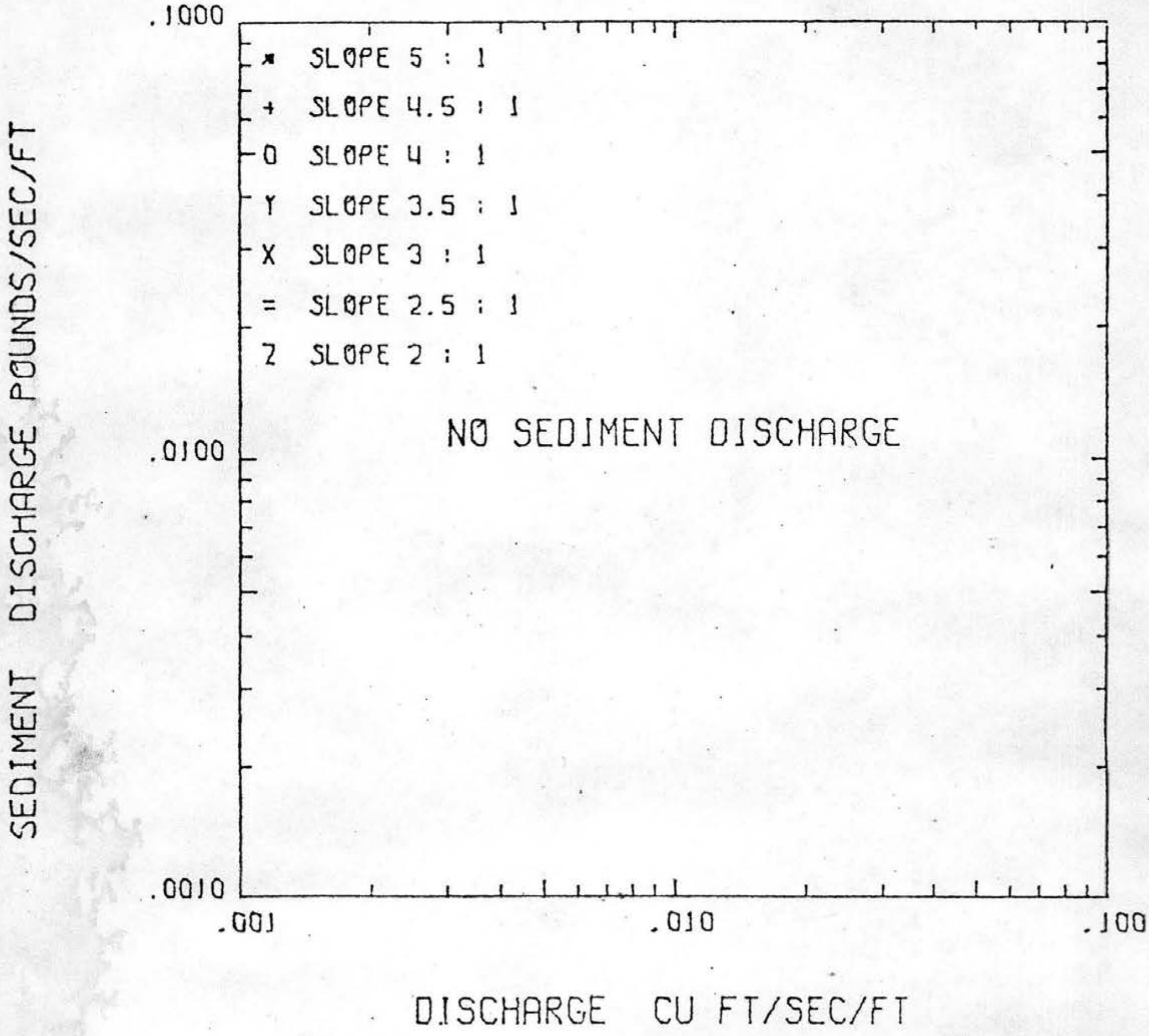

Fig. 60. Sediment Discharge versus Water Discharge for Dense-Vegetation Cut and Fill Slopes and for Sediment Size of 1.5 mm

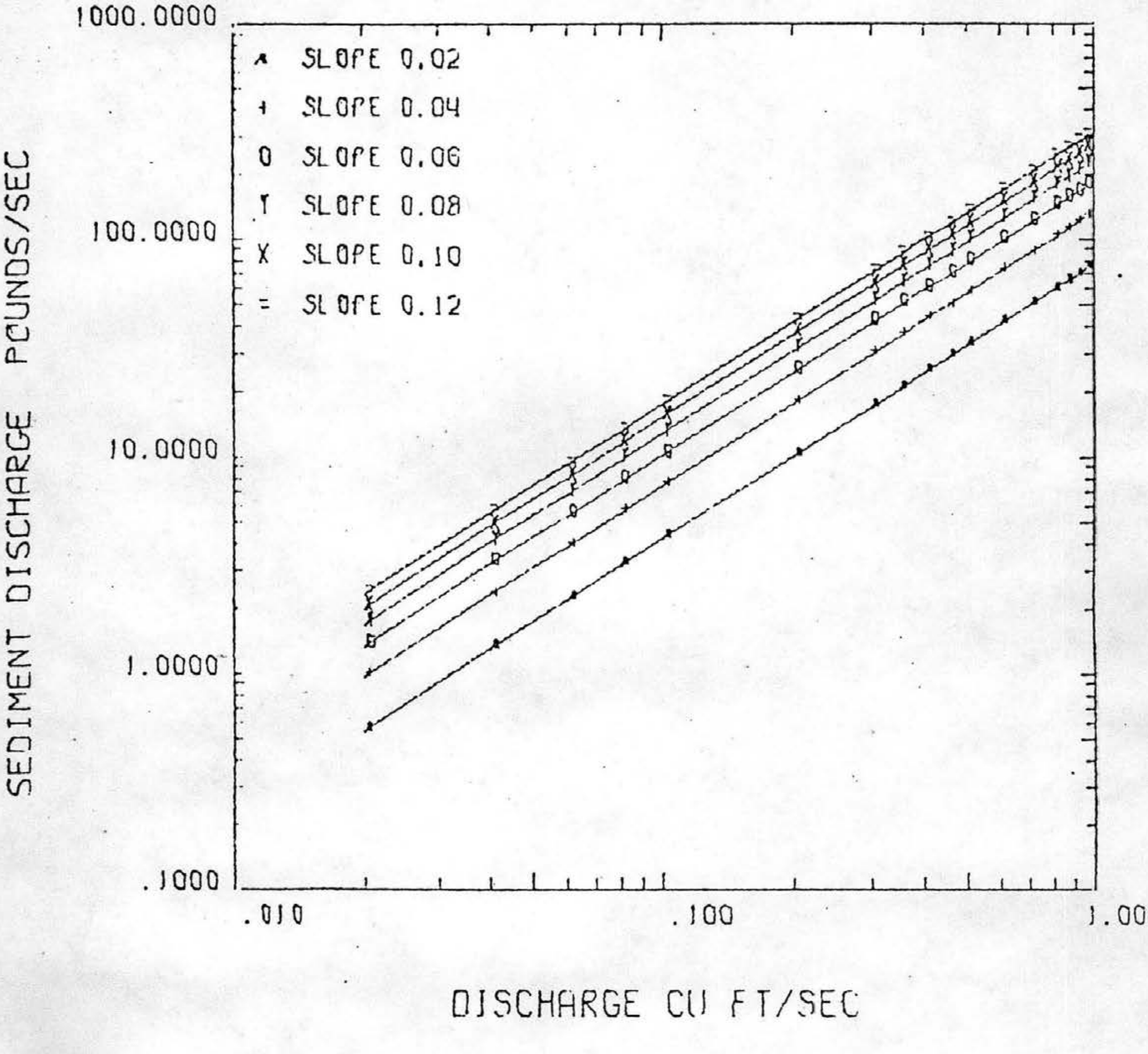

Fig. 61. Sediment Discharge versus Water Discharge for Ditch Flow and Sediment Size of 0.02 mm

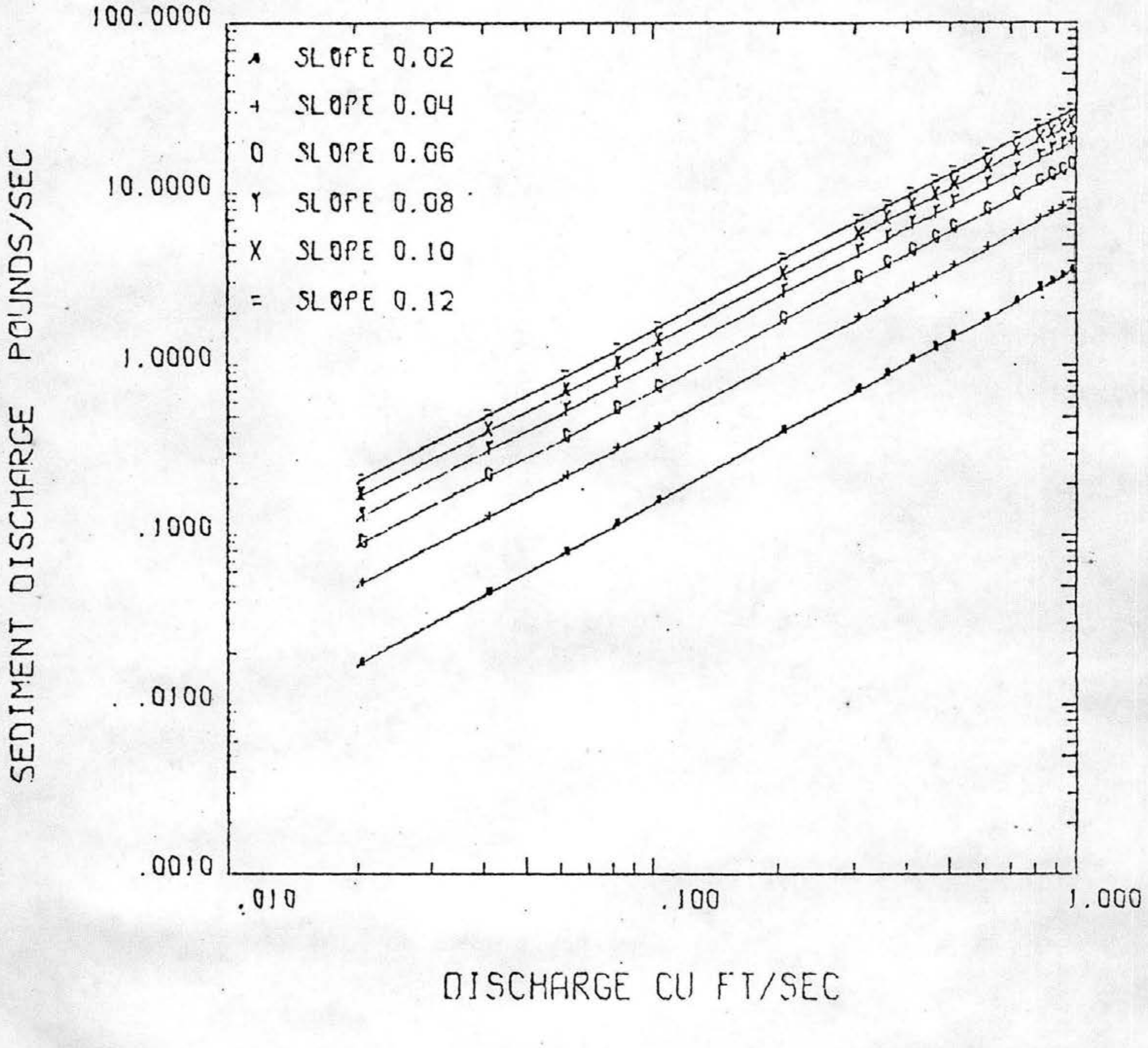

Fig. 62. Sediment Discharge versus Water Discharge for Ditch Flow and Sediment Size of 0.1 mm

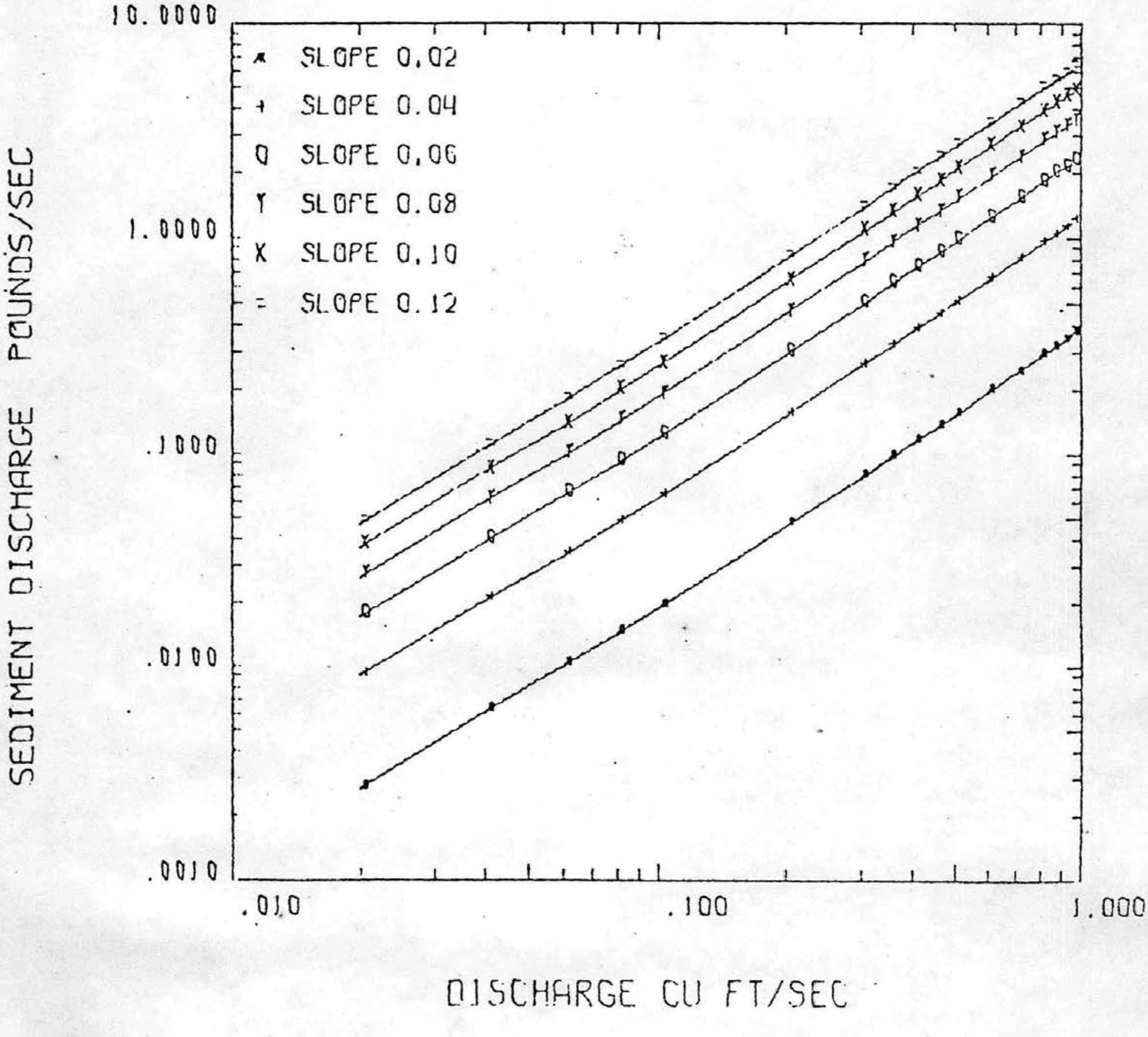

Fig. 63. Sediment Discharge versus Water Discharge for Ditch Flow and Sediment Size of 0.2 mm

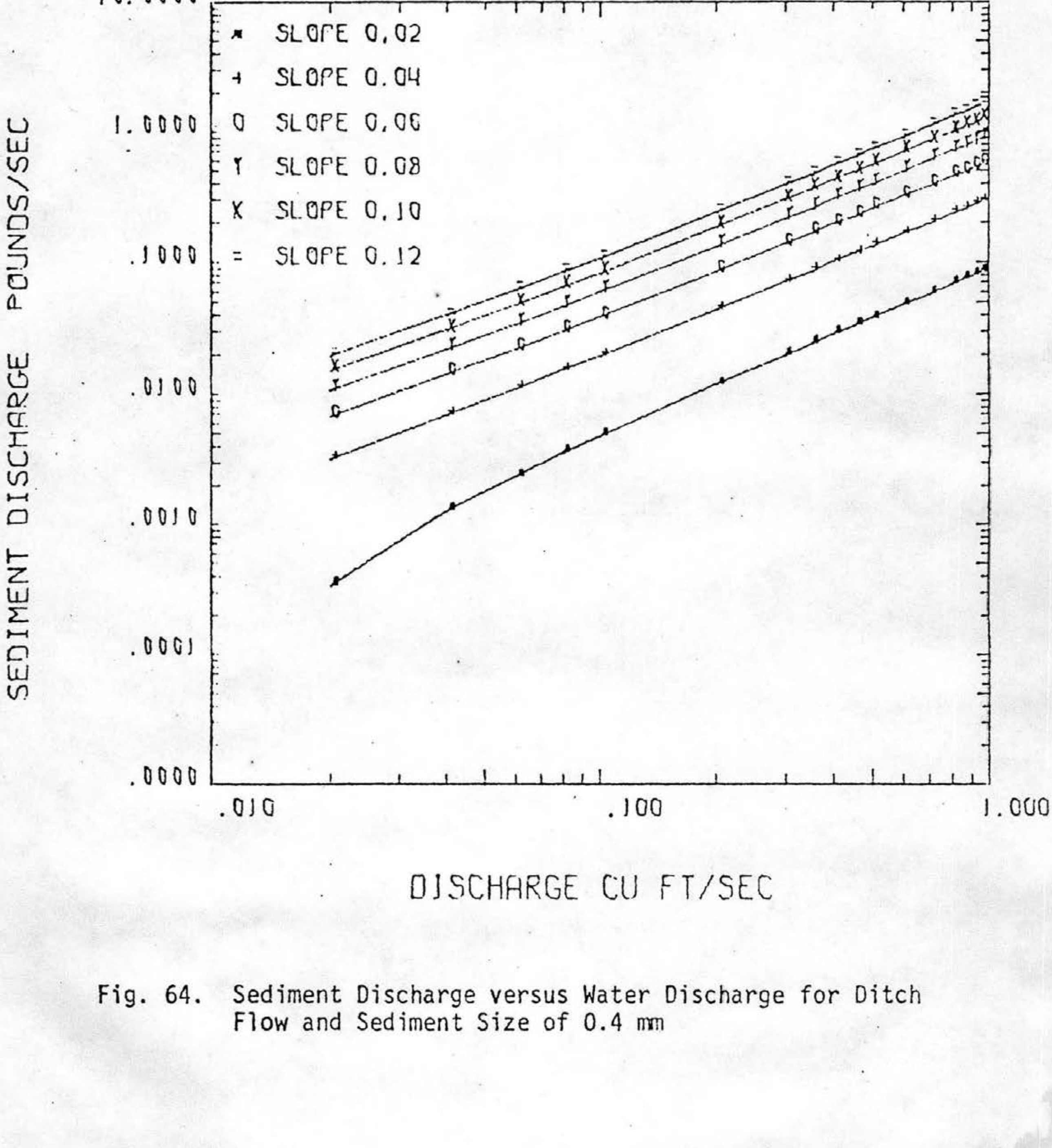

Fig. 64. Sediment Discharge versus Water Discharge for Ditch Flow and Sediment Size of 0.4 mm

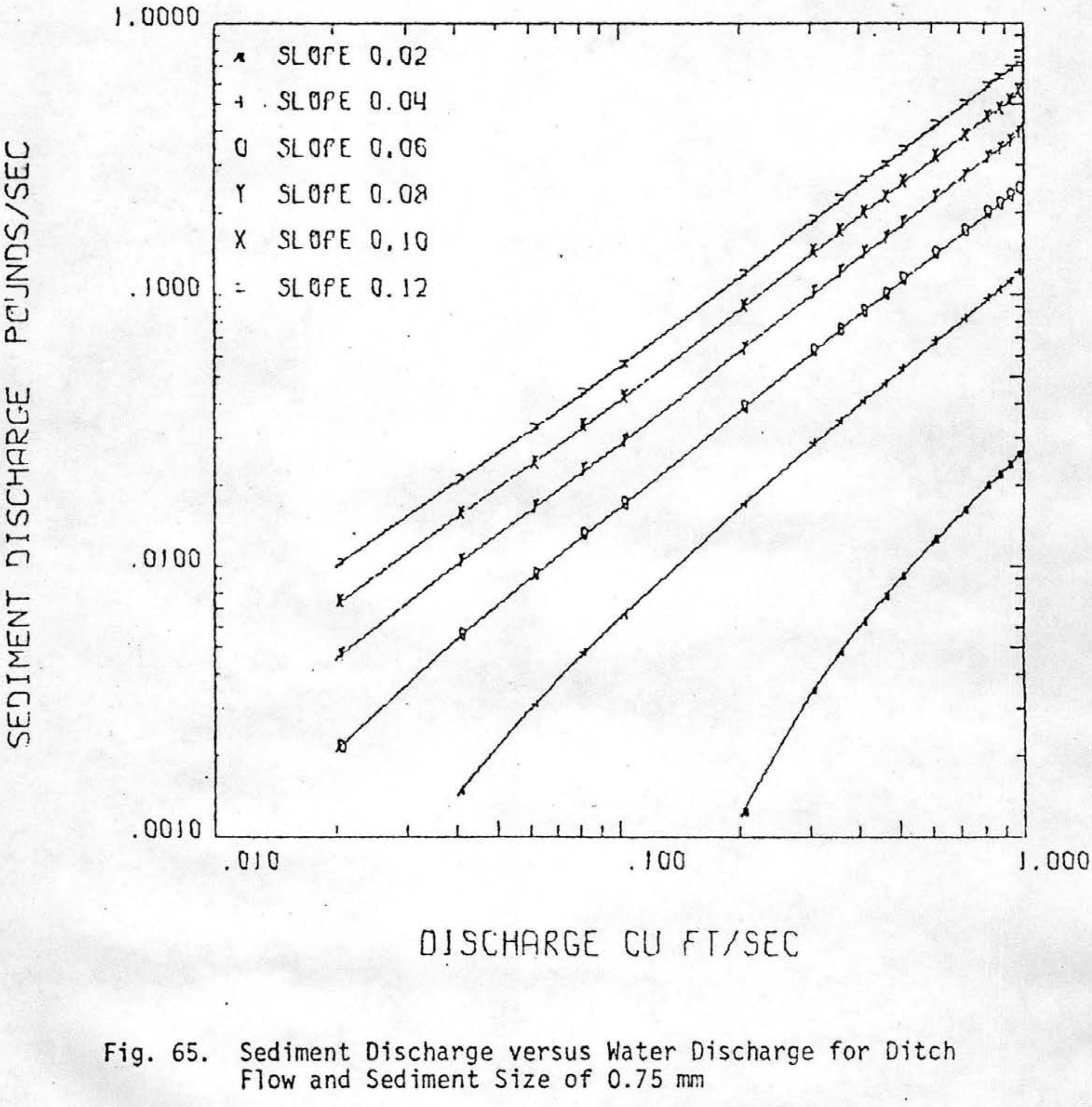

Fig. 65. Sediment Discharge versus Water Discharge for Ditch Flow and Sediment Size of 0.75 mm

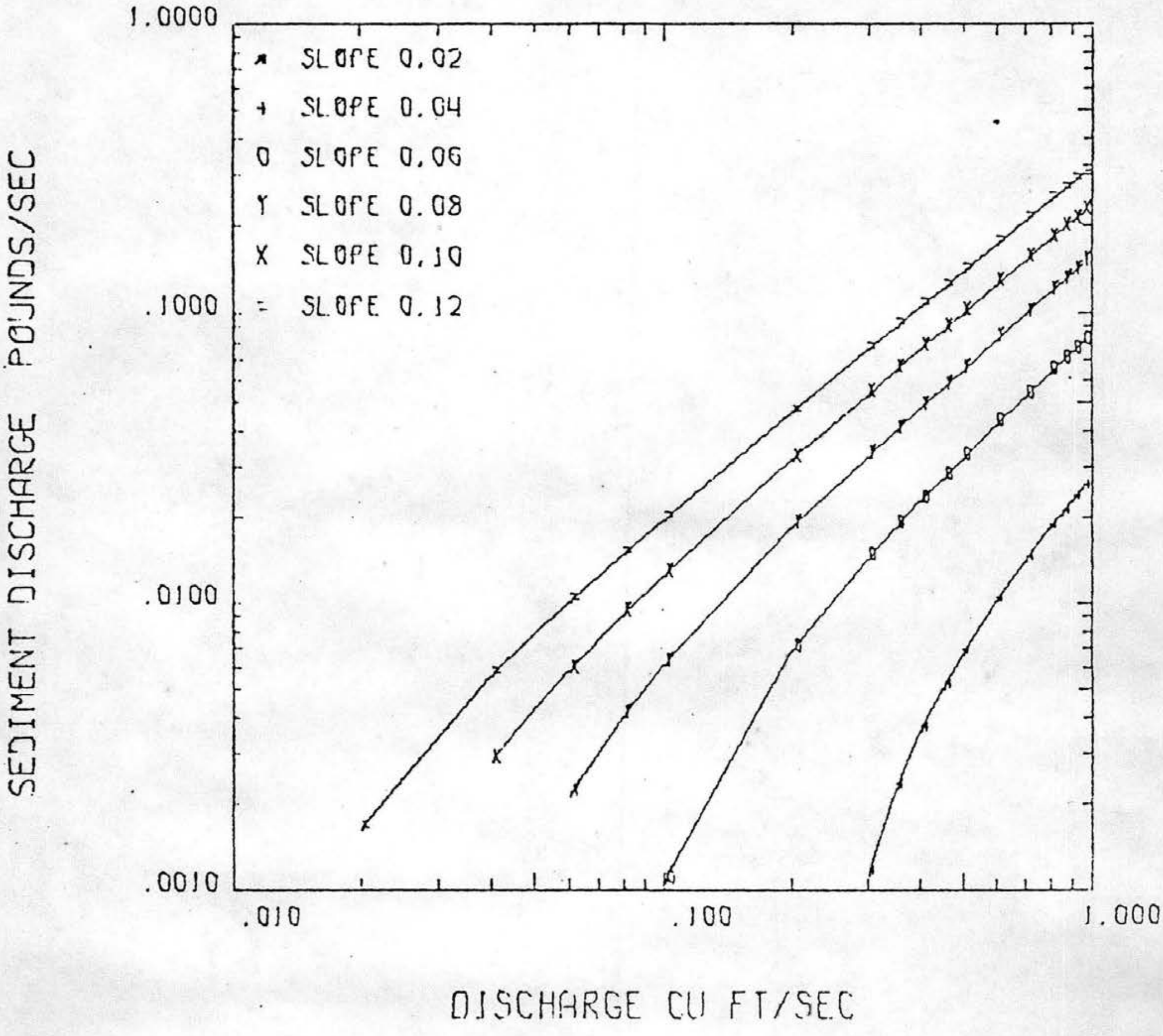

Fig. 66. Sediment Discharge versus Water Discharge for Ditch Flow and Sediment Size of 1.5 mm

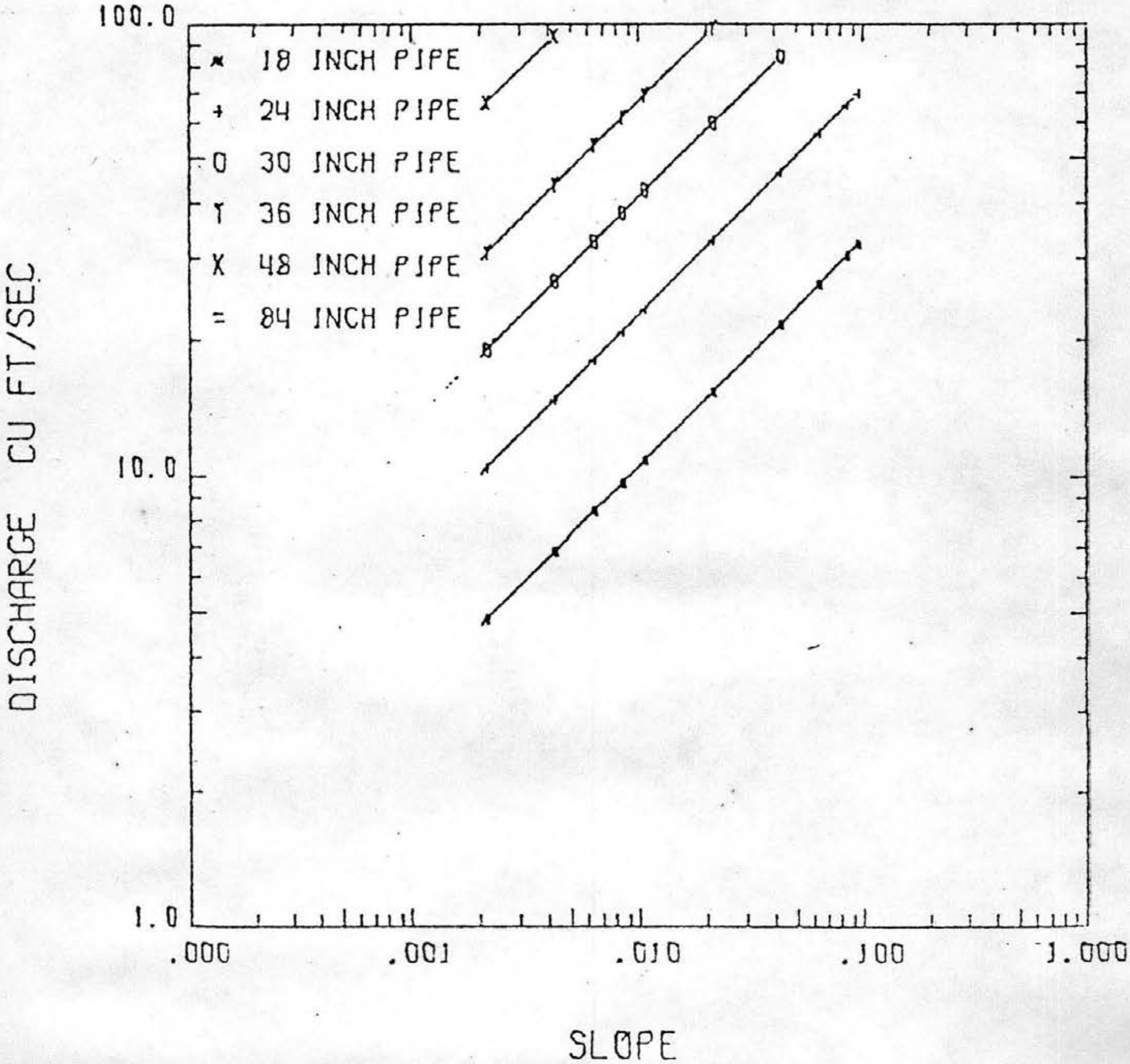

Fig. 67. Water Conveyance Capacities for Various Design Slopes and Sizes of Culvert

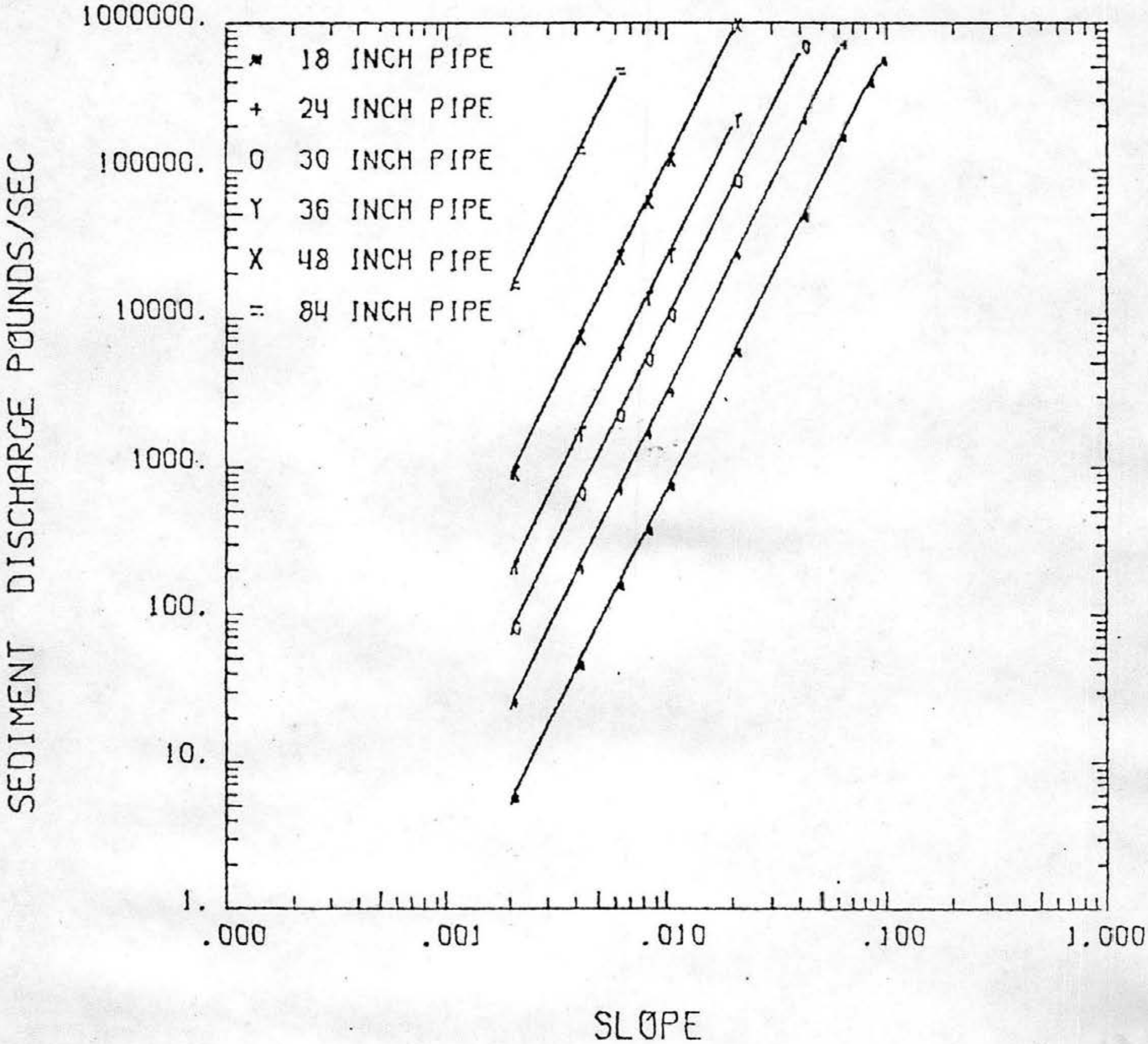

Fig. 68. Sediment Transport in Capacities for Various Design Slopes and Sizes of Culvert and for Sediment Size of 0.02 mm

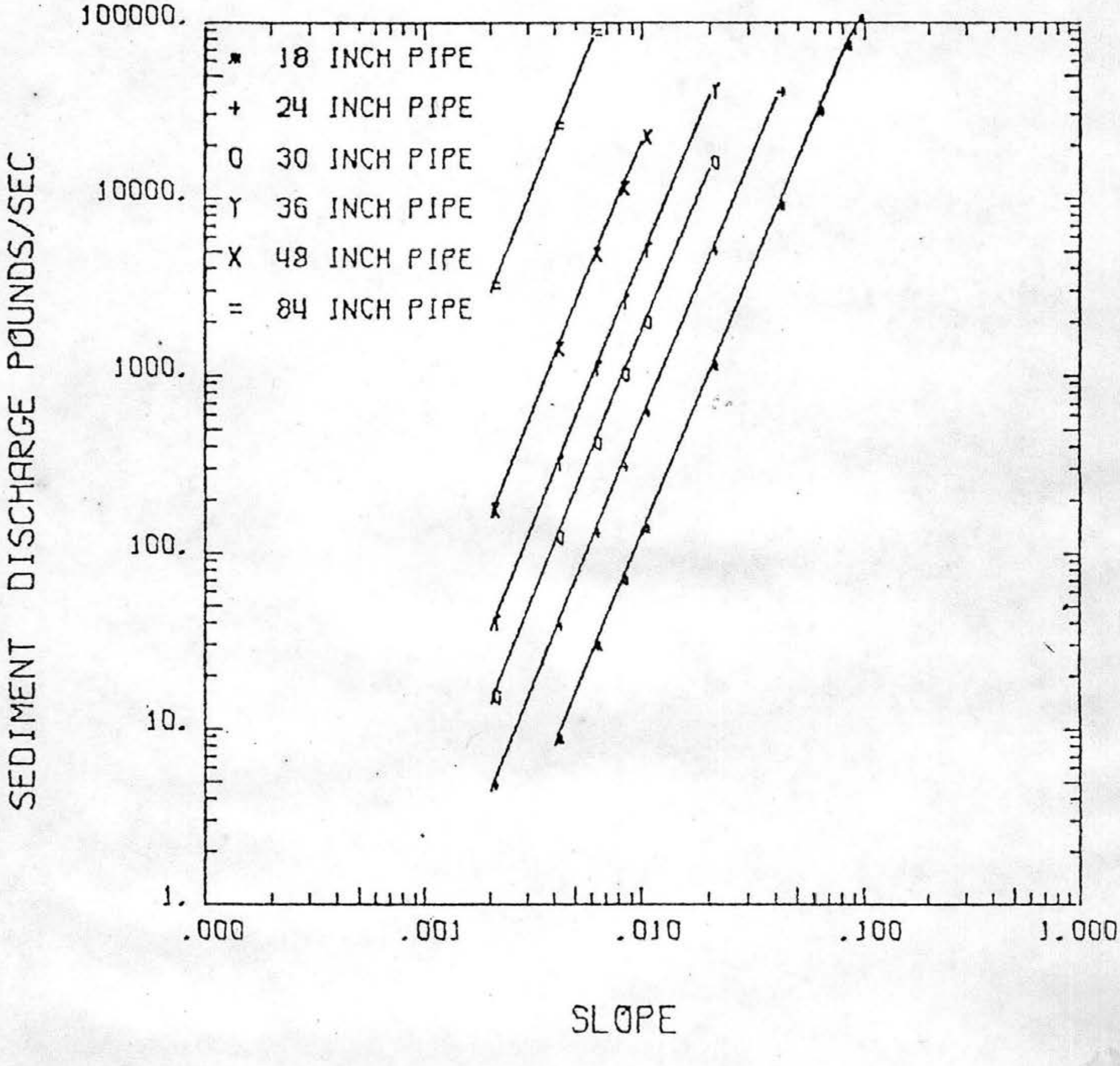

Fig. 69. Sediment Transport in Capacities for Various Design Slopes and Sizes of Culvert and for Sediment Size of 0.1 mm

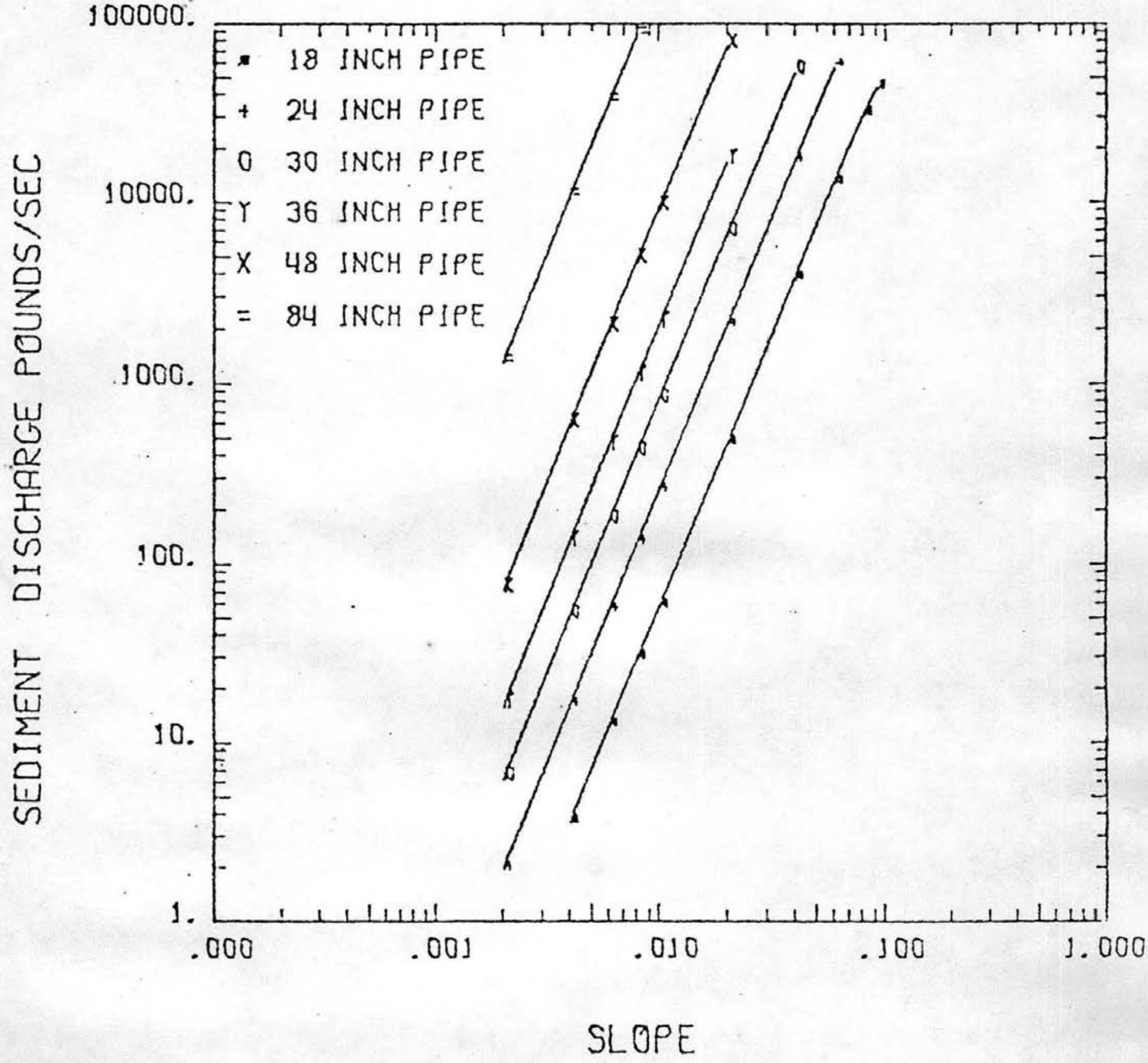

Fig. 70. Sediment Transport in Capacities for Various Design Slopes and Sizes of Culvert and for Sediment Size of 0.2 mm

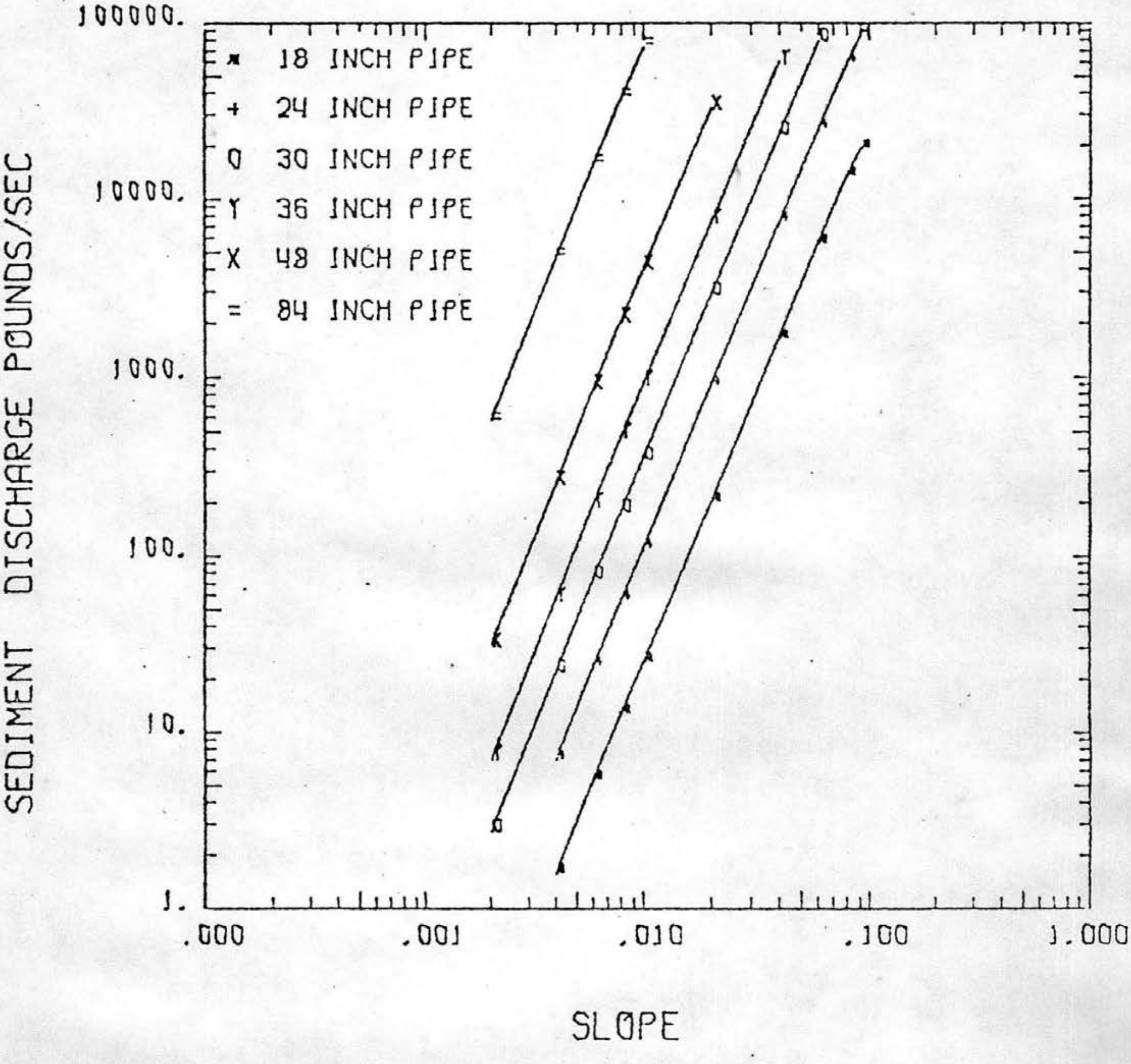

Fig. 71. Sediment Transport in Capacities for Various Design Slopes and Sizes of Culvert and for Sediment Size of 0.4 mm

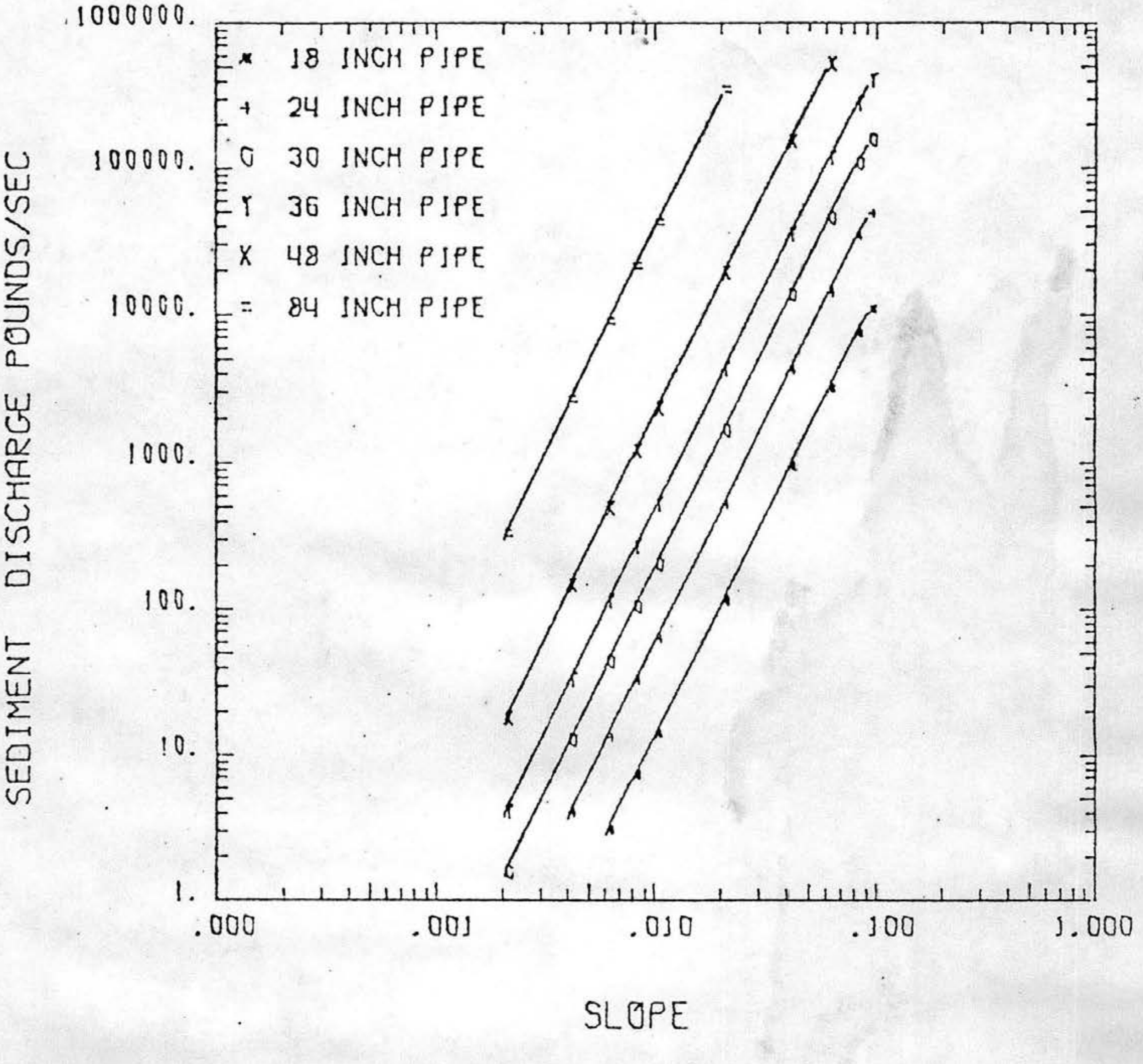

Fig. 72. Sediment Transport in Capacities for Various Design Slopes and Sizes of Culvert and for Sediment Size of 0.75 mm

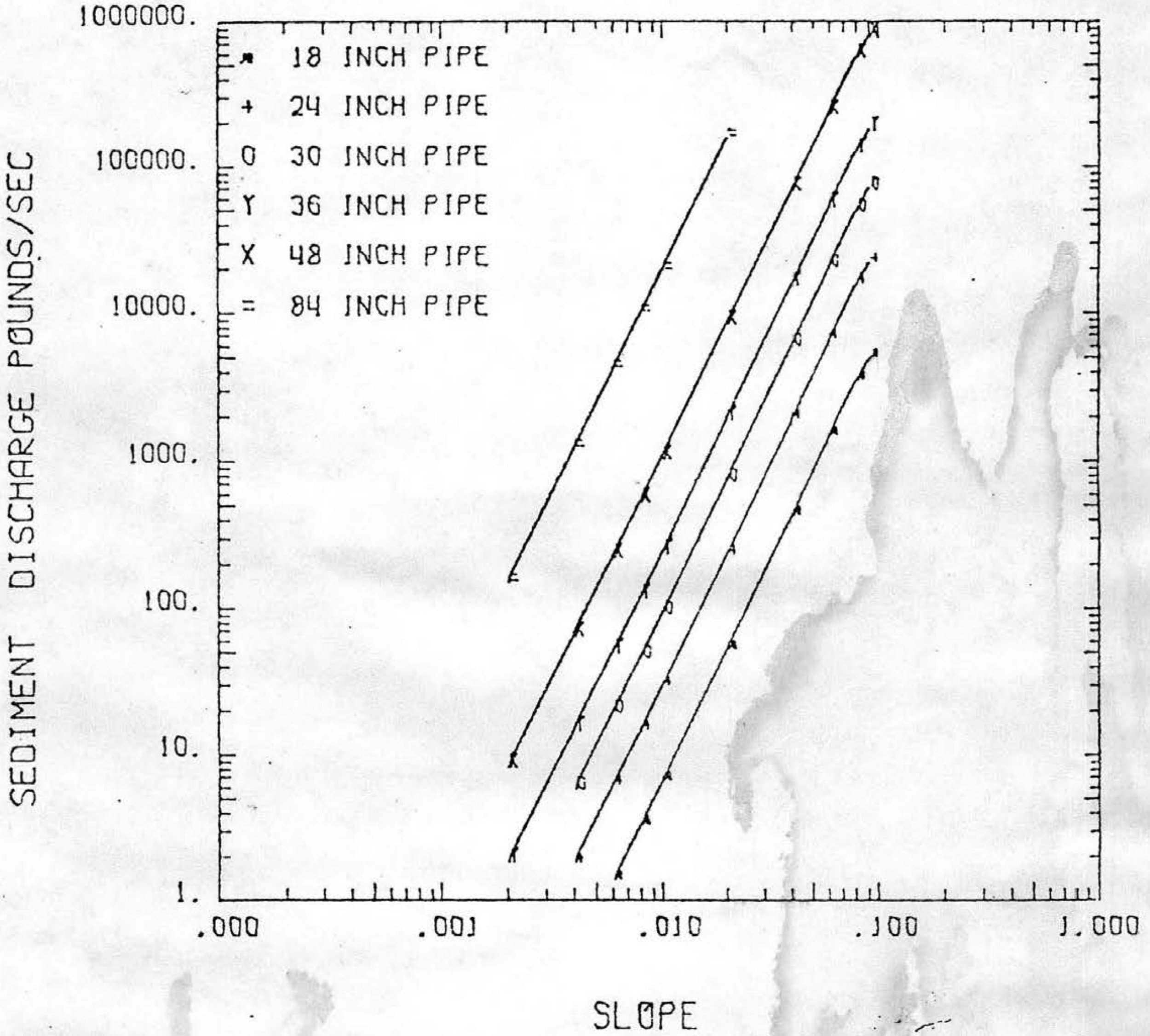

Fig. 73. Sediment Transport in Capacities for Various Design Slopes and Sizes of Culvert and for Sediment Size of 1.5 mm

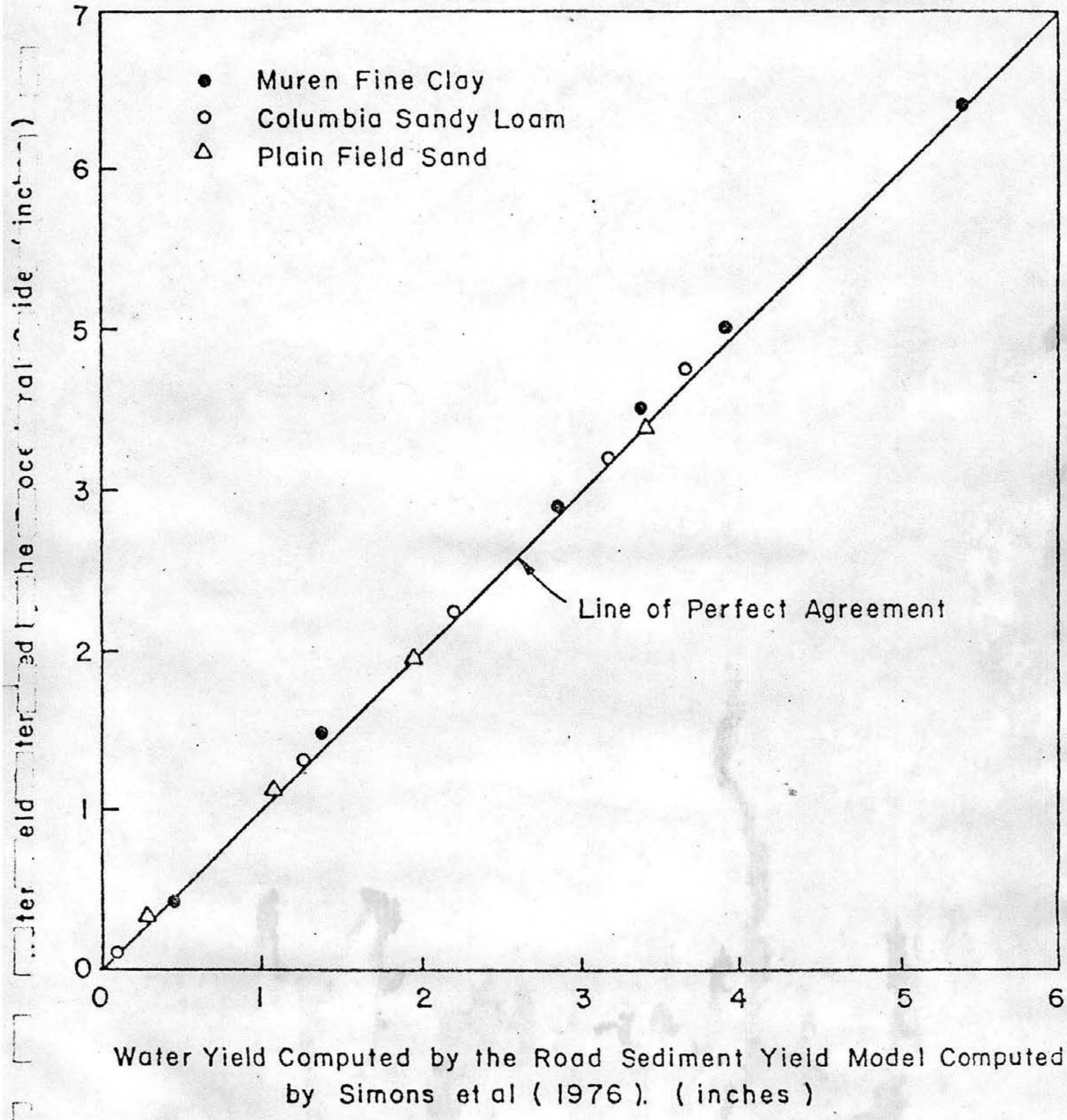

Fig. 74. Comparison of Computed Water Yield

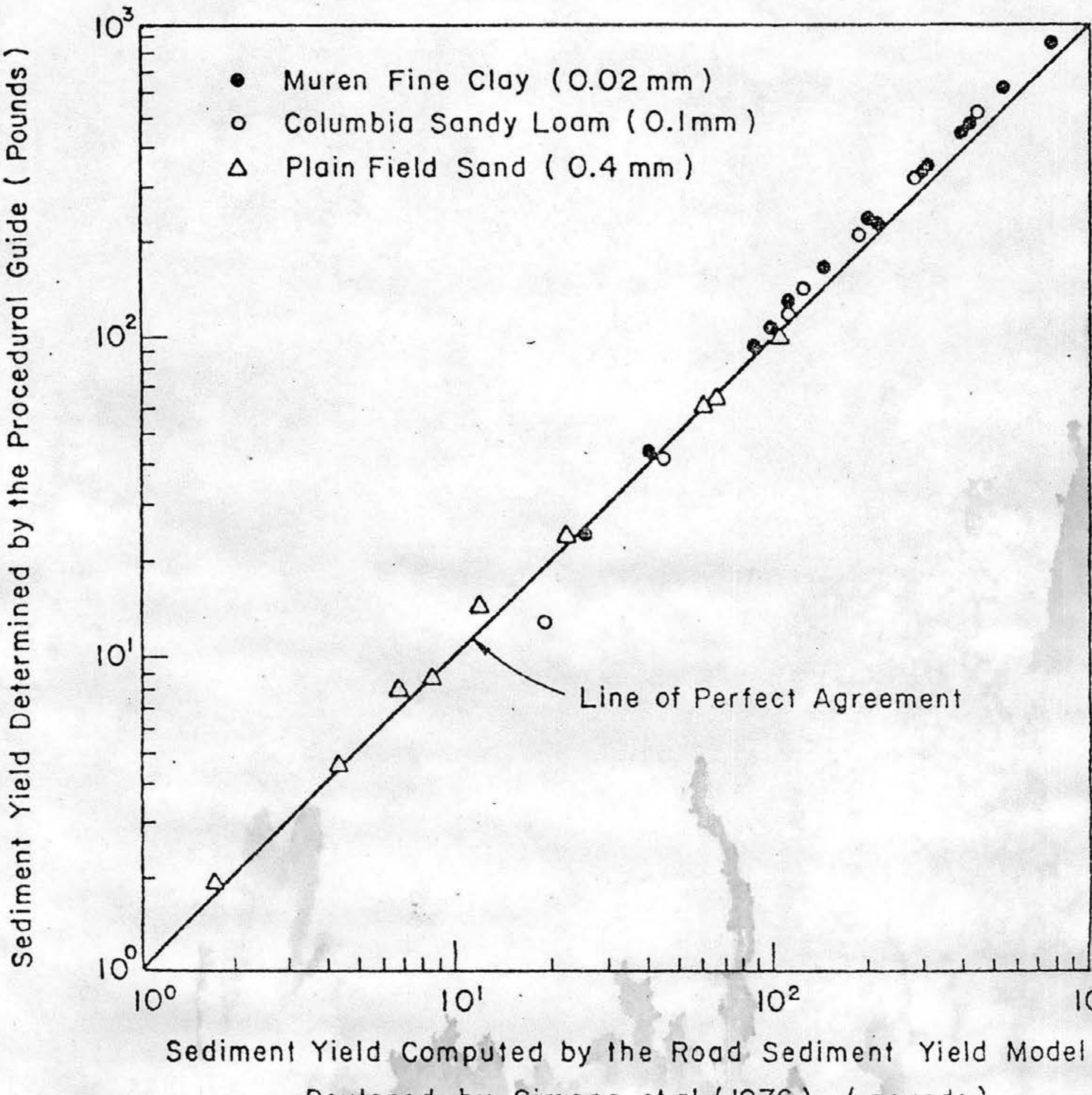

Fig. 75. Comparison of Computed Sediment Yield

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