Applications of Photogrammetry to the Location And Design of Freeways in California

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Aerial photographs are used in practically all of the stages of freeway planning and design in California. Among the uses mentioned for contact prints, enlargements, and mosaics are preliminary location studies, project reports, public meetings, study of design details, determination of drainage areas, materials investigations and right-of-way appraisal, negotiation and condemnation. Data are presented showing the extent to which aerial photographs have been used for route studies in a typical northern California highway district.

Where more specific information is required for route studies, the aerial photographs are supplemented by topographic maps. In areas where they are available, U. S. Geological Survey quadrangel maps will frequently suffice. In other cases reconnaissance-type mapping is obtained by contract. After the general location of the freeway is determined photogrammetric mapping, usually at a scale of 1 in. = 50 ft with 2-ft contours, is obtained for detailed design work. Accurate, adequately monumented control surveys for use in conjunction with the topographic mapping are an important feature of California practice. Specification requirements and other scales of mapping for design use are discussed.

The use of electronic computers for the calculation of earthwork quantities has largely superseded other methods. Terrain and roadbed notes similar to conventional survey notes are prepared by the designer for machine computation. Data for terrain notes are obtained from the large-scale photogrammetric maps. Changes in line or grade can be made by designating horizontal or vertical shifts of the roadbed notes. A few sample cross-sections for illustrative purposes are plotted as required usually at a small scale. Preliminary quantities from aerial contour maps have generally agreed with final quantities within less than 2½ percent. Substantial savings in cost and manpower through the use of photogrammetric mapping and electronic computers are reported.

● IN discussing photogrammetry as related to the location and design of freeways, it is convenient to classify the photogrammetric products used into three types: aerial photographs, reconnaissance mapping, and design mapping. The latter two are used in the stages of a highway project which their names indicate, while the first is used in practically every stage of planning, location, design, and acquisition of rights-of-way.

There are very few freeway projects in California where aerial photographs in the form of contact prints, enlargements, or mosaics do not play an important part. The requirements of a particular project frequently necessitate obtaining several different photographic flights at scales ranging from as small as 1 in. = 3,000 ft to as large as 1 in. = 200 ft. During the period from July 1, 1955 to June 30, 1956, the California Division of Highways contracted for over $80,000 worth of aerial photography in addition to that obtained in connection with topographic mapping.

Preliminary Stages

In the early stages of a project, contact prints are examined stereoscopically to select alternate routes for further study and to determine which of those routes is the best. The small scales (1 in. = 800 ft to 1 in. = 2,000 ft) are generally used in rural areas where there is little development or where a wide band of alternate routes must be considered, while larger scales (1 in. = 400 ft to 1 in. = 600 ft) are used in urban areas. If the project is in mountainous terrain, requiring an approximate profile for preliminary study, the contact prints are used with a stereoscope and parallax bar to determine relative elevations.

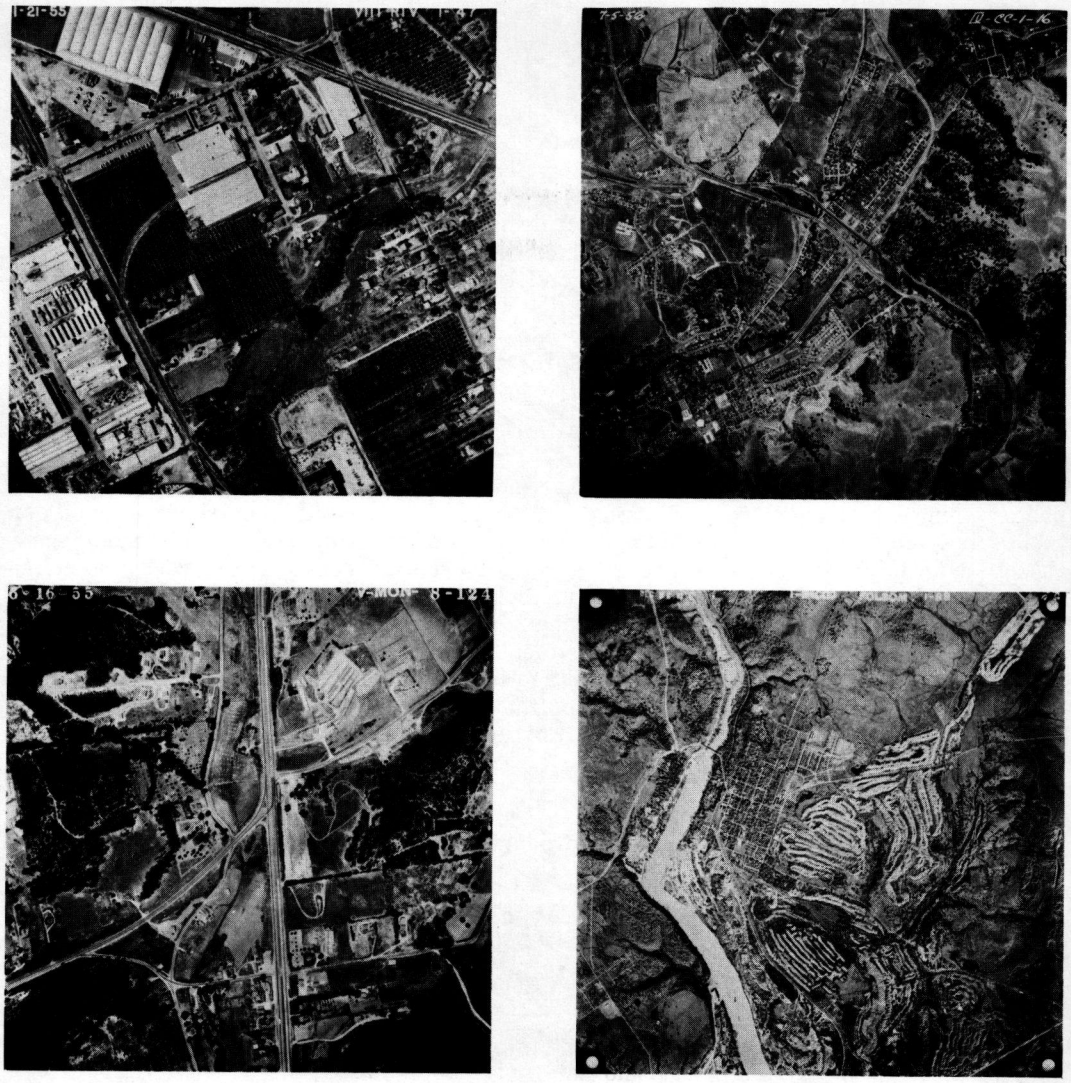

Figure 1. Contact prints at some of the scales being used for freeway planning and design. Scales of original photographs: upper left, 1 in. = 250 ft; lower left, 1 in. = 400 ft; upper right, 1 in. = 1000 ft; lower right, 1 in. = 2000 ft.

Small-scale contact prints or enlargements provide the best possible medium for the study of access conditions and tentative interchange locations, while larger-scale photographs are invaluable for making right-of-way estimates. Diazo prints of mosaics, showing the various alternate routes and locations of proposed interchanges, are used in practically all reports which summarize route studies on a particular project.

Public Meetings

A very important phase in the planning of the freeway program is the holding of public meetings and hearings on every project involving even minor relocation. Aerial photographic mosaics, showing the routes under consideration and proposed interchange locations, are considered an absolute necessity for such meetings. The mosaics are generally of the semi-controlled type with a rather low order of accuracy. Scales used range from 1 in. = 200 ft to 1 in. = 1,000 ft, depending on the size of the project and the extent to which the area is developed. The photographs are also useful for discussions

with individuals concerning specific property and proposed freeway locations.

Design

In the design stage, study of large-scale contact prints or enlargements gives the squad leader and the designer an added knowledge of the project which could not be obtained in any other way. They also serve to reduce greatly the number of field trips which would otherwise be required. As it is impossible to show all of the detail available from the photographs on a topographic map, the designer frequently uses diazo prints made from positive enlargements on film to lay out and study tentative interchange designs and other details.

Contact prints, both large and small scale, are used for determining drainage areas, locating source of granular material, and for studying potential slide conditions and other foundation problems.

Right-of-Way

In the important phases of the appraisal and acquisition of rights-of-way, aerial photography is proving to be increasingly valuable. Large-scale enlargements and contact prints are used for appraisal and discussion with the property owner during negotiation, both in urban and rural areas. Where it becomes necessary to resort to condemnation, large-scale enlargements are used to show the court the details of the area to be taken and, in the case of large holdings, small-scale enlargements are used to show the relation of the proposed improvement to the entire property. Oblique aerial photographs have also been used to advantage in condemnation cases. Large-scale photography is frequently obtained on metropolitan freeway projects immediately before the start of right-of-way negotiation so it will be available for possible condemnation cases at a later date.

Location Studies

The second type of photogrammetric products, reconnaissance mapping, is used for

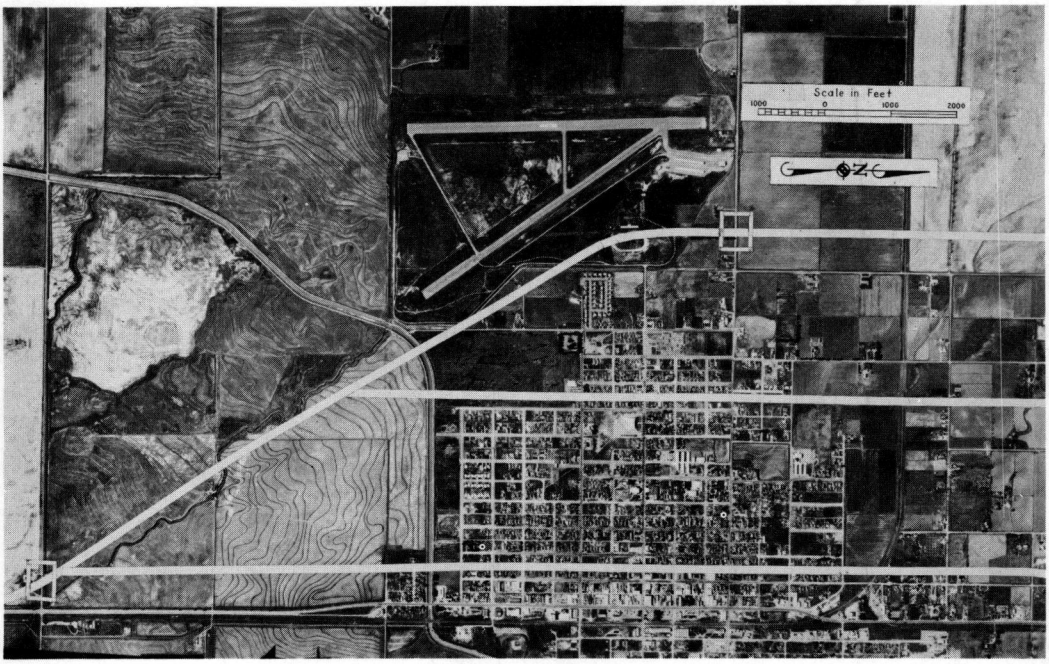

Figure 2. Several possible locations have been shown on this mosaic for a public presentation of route studies.

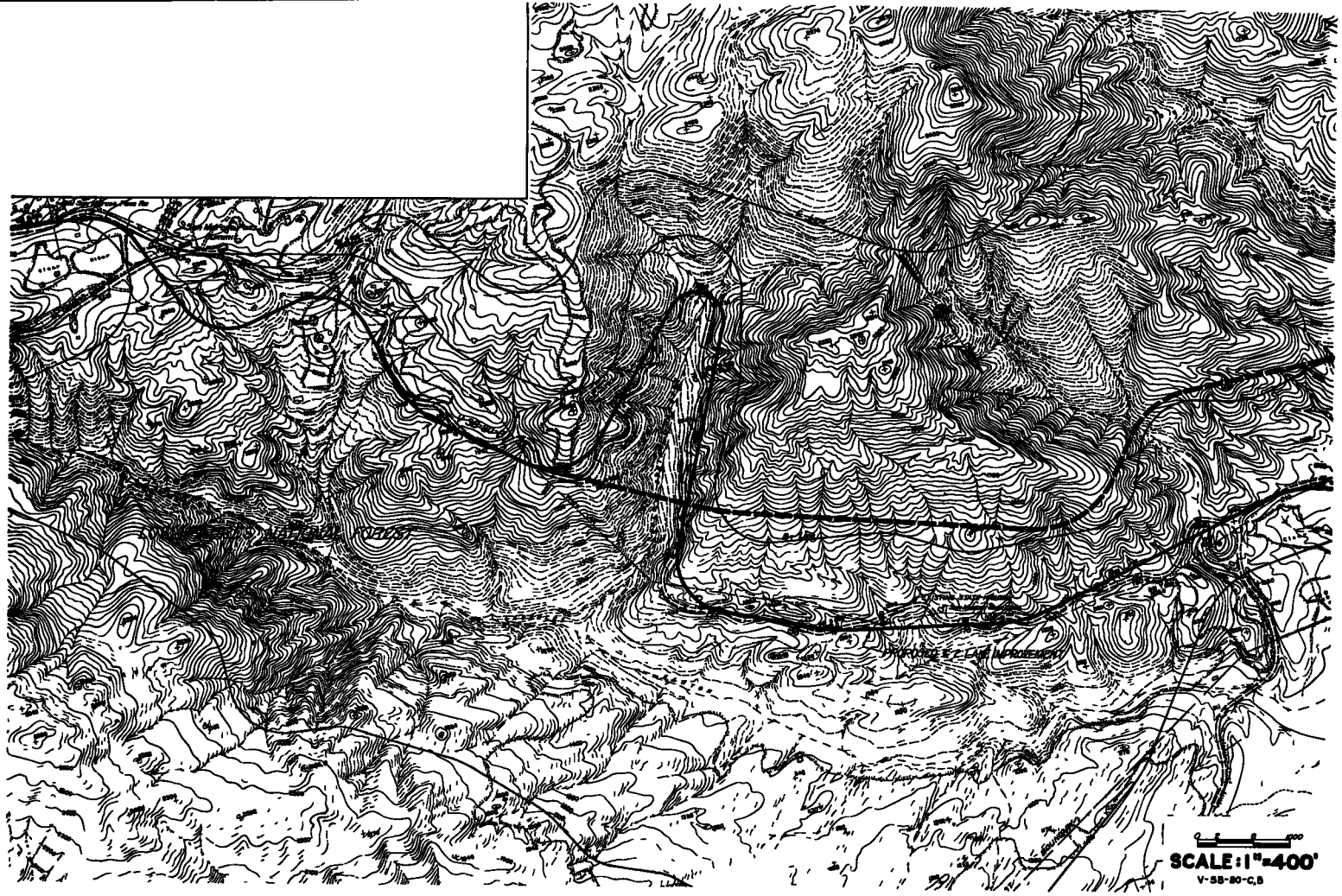

Figure 3. Photogrammetric mapping of this type is used for reconnaissance studies of several alternate routes in rugged terrain.

location studies where more than one possible route must be considered, where the terrain is such that excavation quantities are an important factor in the location, or where grade controls might govern. The important difference between aerial photographs and either reconnaissance or design mapping is that the latter is accurate in scale and is based on an actual field survey, with this survey being used to control the scale of the maps and the differences in elevation shown.

For reconnaissance work, the highway engineer planning to use photogrammetric mapping has a choice of several products. In areas where they are available, U. S. Geological Survey quadrangel sheets at a scale of 1 in. = 2,000 ft with contour intervals of 20 or 40 ft are one of the most effective tools of the location engineer. When used in conjunction with stereoscopic study of contact prints, the maps provide the answer to many location problems.

An excellent example of the effectiveness of aerial photography and Geological Survey quadrangle mapping in reconnaissance studies is shown by data concerning such studies in District II of the California Division of Highways, located in the extreme north-central and northeast portion of the state. In the period from August 1955 to August 1956, the District Planning Department studied the relocation of 183 miles of highway. Of this total, 123 miles were planned on either a full freeway or expressway basis. The studies involved consideration of a total of 567 miles of alternate routes of which 168 miles were in rugged terrain and included 273 bridge sites and 112 interchanges. The following tabulation shows the various methods used in the studies:

	Miles	Percent
Aerial photographs only	295	52
Photographs and U. S. G. S. quadrangle maps	125	22
Photographs and reconnaissance mapping (1 in. = 400 ft)	80	14
Other methods	67	12
Total	567	100

The fact that they were able to complete 52 percent of their studies with aerial photographs alone and an additional 22 percent with aerial photographs supplemented by Geological Survey maps is very impressive when it is considered that District II includes some of the most difficult, mountainous terrain in the state from the standpoint of freeway location.

Reconnaissance Mapping

Where conditions require a larger scale, or where U. S. Geological Survey mapping is not available, form line mapping from either existing or new photography is frequently obtained for reconnaissance work. A reasonably accurate map at 1 in. = 400 ft with 20-ft contours can be obtained from existing Commodity Stabilization Service photography at a scale of 1 in. = 1,667 ft, supplemented by a minor amount of ground control. In some cases existing road surveys or U. S. Geological Survey data will provide sufficient control. Such mapping is generally obtained on force account or plotter rental basis from mapping contractors and is usually confined to relatively small areas.

Where it is necessary to study several alternate routes covering a wide band of rugged terrain, the usual practice is to contract for reconnaissance mapping in the same manner as for design mapping. Scales used have ranged from 1 in. = 200 ft to 1 in. = 500 ft, with contour intervals of 5, 10, and 20 ft. Here again the larger scales are associated with intensive land use and the smaller scales are used in rural areas. Such a map at 1 in. = 400 ft with 20-ft contours will cover an area over 2 miles in width with a single strip of photography.

The use of reconnaissance mapping has practically eliminated the necessity for making preliminary field surveys of several alternate routes in order to determine the best location. Such mapping has been obtained for conditions ranging from metropolitan freeways in the larger cities to freeway relocations in the mountainous and heavily-timbered regions of northern California.

Design Mapping

After the route of the highway has been determined within rather close limits by one of the methods previously discussed, the next step is to obtain large-scale, small contour interval, photogrammetric mapping for detailed design of the freeway facility. The mapping is usually confined to a single strip of photography and is from 1,000 ft to 1,500 ft in width to allow for minor adjustments in the exact location. Additional width is frequently obtained at traffic interchanges. The scale found suitable for most conditions is

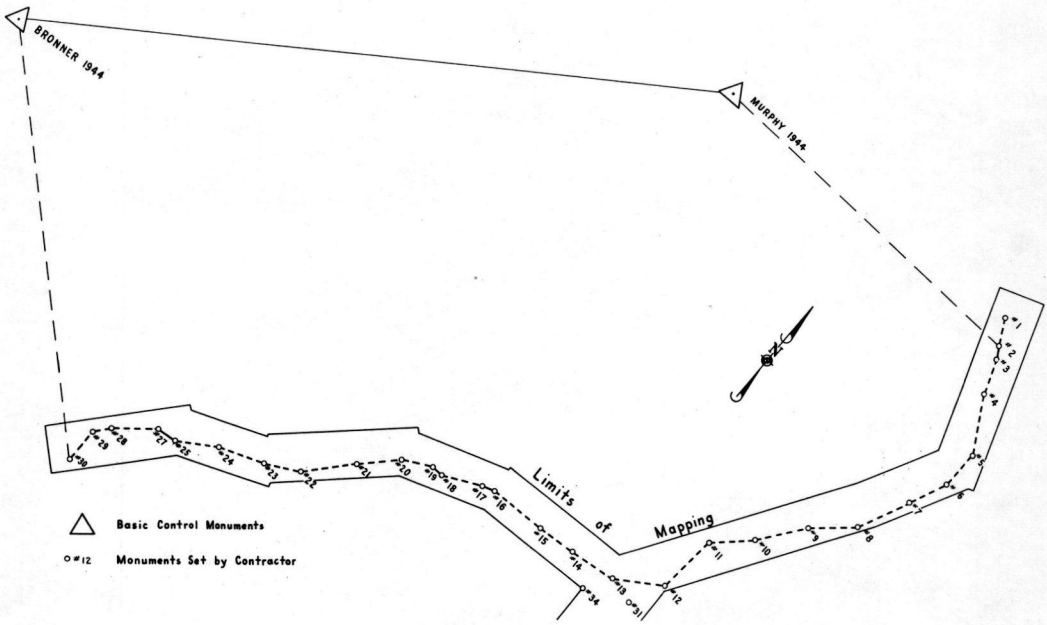

Figure 4. The primary ground control survey for an 8-mi design mapping project is shown in the upper diagram. The overlapping aerial photographs below illustrate the photo control points established for one of the stereoscopic models.

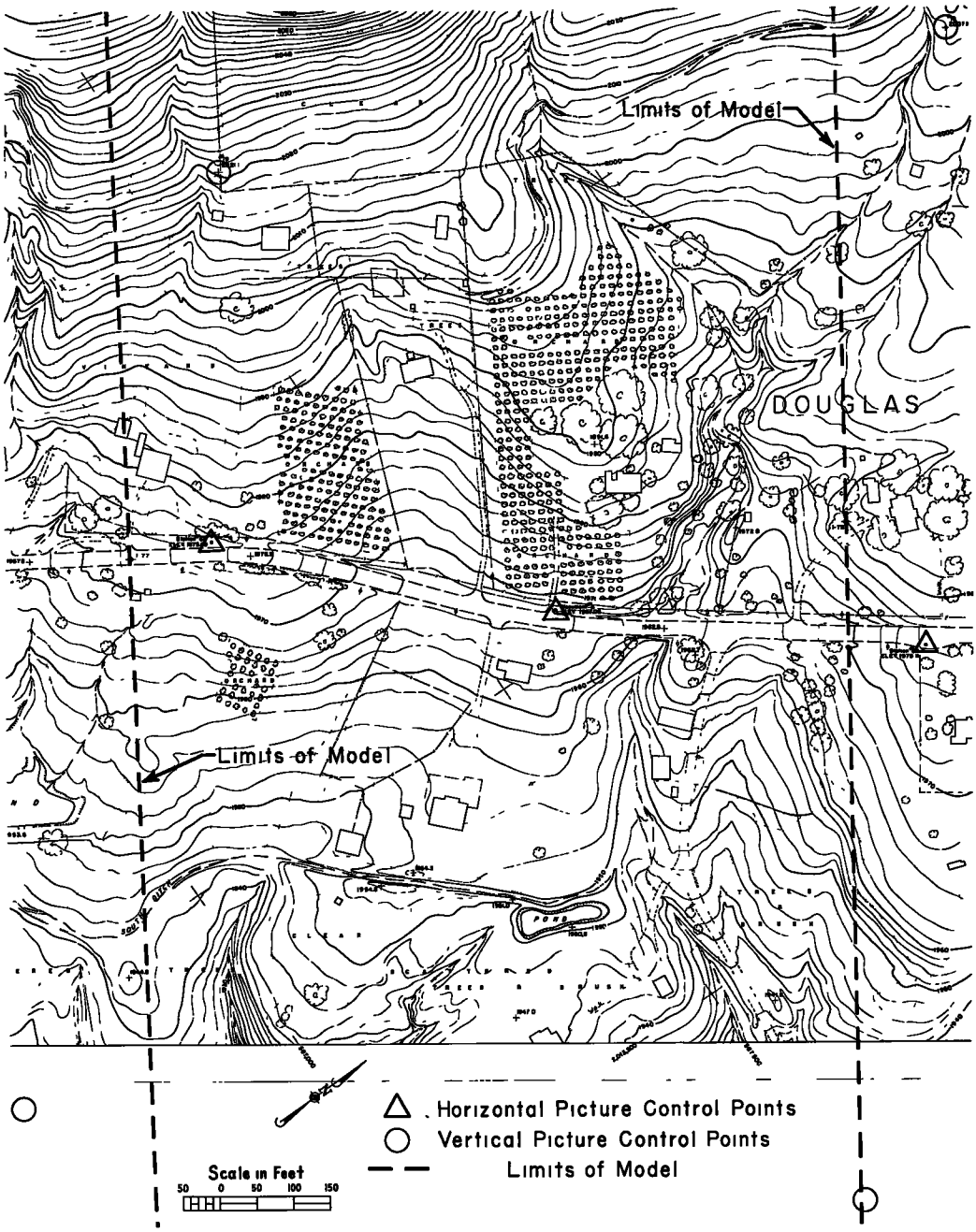

Figure 5. This portion of the final map at a scale of 1 in. = 50 ft with 2-ft contours was compiled from the photographs shown in Figure 4. Monument No. 8 shown on the control diagram in Figure 4 was used as the horizontal picture control point near the center of the model.

1 in. = 50 ft with a contour interval of 2 ft. Such mapping is used for the design of facilities ranging from metropolitan freeways to rural expressways in desert, mountainous, or agricultural terrain.

One of the most important features is the requirement for adequate control surveys, properly monumented at intervals ranging from 1,000 ft to one-half mile, as the basis for the topographic maps. Such surveys are generally made to second-order accuracy and are based on the California Coordinate System. They are carefully planned and include monumented control not essential for strictly mapping use. Complete survey notes, including data on adjustment of observed values, are furnished by the mapping contractor. The monuments may be key property corners or new points selected for later use by the Division of Highways. They will be used for any supplemental surveys that may be required, including property corner ties, and will be the basis for staking the projected final line in the field.

This practice results in maps from which it is possible to project the located line with computed ties to points of known position in the control net, complete the design, compute quantities, write deed descriptions for right-of-way, and advertise the construction contract with a minimum of additional field survey work. In some cases the located line is not run in the field until the right-of-way has been purchased and completely cleared. With key property corners and other permanent monuments, selected by the highway engineer, tied in by the survey and the entire survey based on the California Coordinate System, the located line as finally run in the field closes without difficulty.

Mapping Specifications

Other steps in the making of photogrammetric maps for design use include photography, picture point control, map compilation and, in some cases, field editing by the mapping contractor to determine the position of contours and planimetric features obscured by ground cover. To insure map accuracy satisfactory for detailed design work, it has been found advisable to specify a minimum of three horizontal and five vertical picture points for each model to aid in properly orienting the photographs in the stereoplotting equipment. The specifications also limit the ratio between photography and final map scale for various stereo-plotting instruments.

While maps at 1 in. = 50 ft with 2-ft contours are satisfactory for most projects, there are some conditions where other types of mapping are best suited for design purposes. In comparatively level terrain for example, even 1-ft contours are not entirely satisfactory for accurately depicting the ground surface. In such cases, maps are obtained at 1 in. = 50 ft with a grid of spot elevations at 100-ft intervals in lieu of contours in areas where 2-ft contours would be more than 100 ft apart. The specifications require that the spot elevations by expressed to the nearest 0.1 ft, and that 70 percent be within 0.5 ft of their true elevation, and all be within 1.0 ft. While closer results than this can undoubtedly be obtained under ideal conditions, the specifications are realistic in recognizing the difficulties of extreme accuracy in photogrammetric measurements due to irregularities in the ground surface and the effects of grass and other ground cover.

On projects where the terrain is quite rugged or where the ground surface is extremely rough or obscured by brush and timber to the extent that 2-ft contour mapping by photogrammetric methods would be impracticable, design mapping at a scale of 1 in. = 100 ft with 5-ft contours is frequently used. The contours are supplemented with spot elevations accurate to 1 ft in areas so level that 5-ft contours would not depict the topography accurately.

Use of Maps in Design

In the calculation of earthwork quantities from photogrammetric maps, the use of electronic computers has almost completely supplanted both the contour grading or horizontal slice method and the conventional cross-section and planimeter method. The method used involves the submission of terrain and roadbed notes to the tabulating section for computation. The terrain notes, in the conventional form of field cross-section

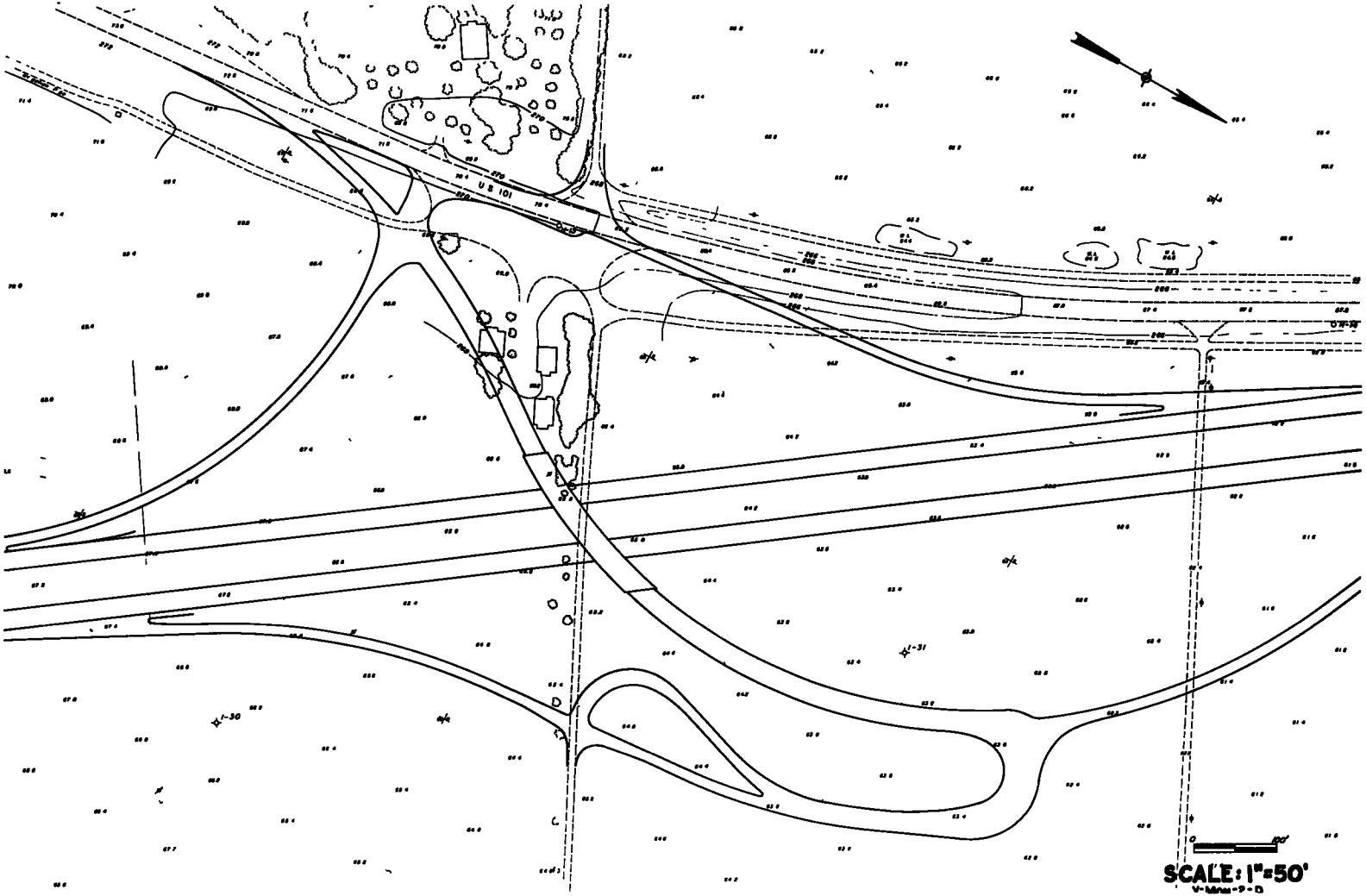

Figure 6. A grid of spot elevations at 100-ft intervals is used in lieu of contours for design mapping in comparatively level terrain.

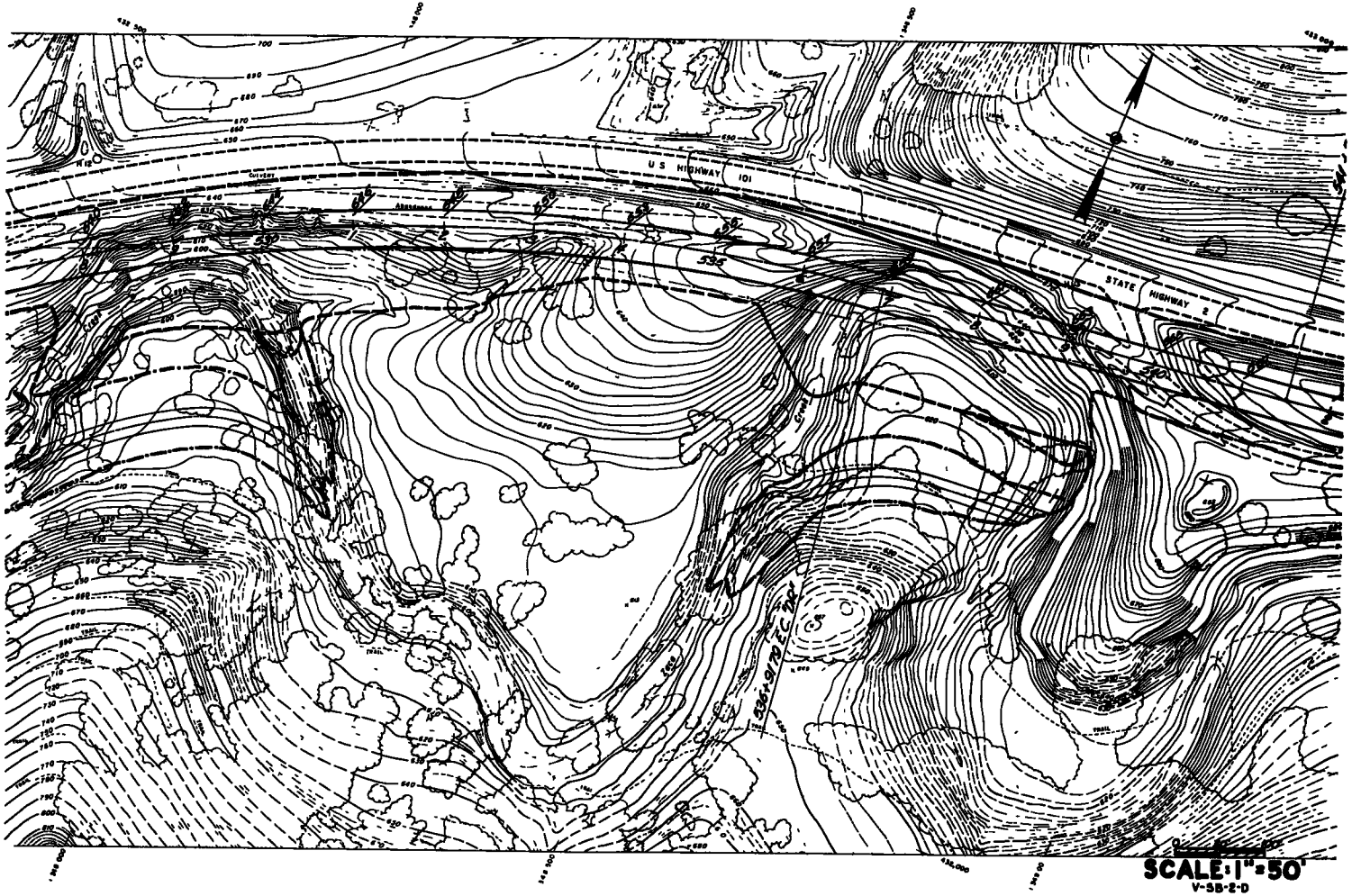

Figure 7. Outer limits of cut and fill slopes obtained by machine computation have been drawn on the contour map preparatory to laying out the right of way lines and designing the drainage.

notes, are taken from the contour maps. Roadbed notes, prepared in similar form, show the various breaks in the templet, which may include ditches, benches, etc., and rates of cut and fill slopes. Data furnished the designer by machine computation include cut and fill quantities, mass diagram ordinates, and distances out to catch points of cut and fill slopes.

The basic problem in design is to establish the line and grade to fit previously determined controls and design standards in the most economical manner. Preliminary computations for earthwork quantities involved in this projection work can be made by any one of various short-cut methods. At the stage of projection selected by the designer as the most efficient to start using machine computation, roadbed and terrain notes are developed for submission. After the results of the machine calculation are received and studied for balance and other factors, adjustments of line and grade are made by the designer if necessary. New roadbed notes or instructions to use the original notes with designated horizontal or vertical shifts are then submitted and combined with the previously submitted terrain notes for machine computation. By this method any number of variations of line and grade can be investigated in a fraction of the time formerly required.

With line and grade established, either in final form or within rather narrow limits, the designer plots cut and fill catch points furnished by machine computation on the contour map and lays out the right-of-way lines. Up to this point the center line has generally been in graphic form only on a print or transparency of the contour map which is being used as the design hard copy. The designer is then ready to establish the line mathematically by scaling the coordinates of various points on the projected line which may be used as controls. These data are set up on traverse sheets for machine computation of the actual traverses. The center line will subsequently by staked in the field by computing ties from monuments, whose position has been established by the mapping contractor, to convenient points on the calculated center line. As the contractor's basic surveys which included these monuments have been made to second-order accuracy, recalculation or adjustment of the center line traverse is seldom if ever required during the field staking.

At this point the designer is ready to plan and design the drainage for the project, using the contour map in lieu of the usual hard copy and cross-sections. As he is not restricted to cross-sections taken at right angles to center line, he generally plots a section on the skew proposed for the culvert at each location where cross drainage is required. These sections will be used for the calculation of structure excavation and back fill and ditch and channel excavation quantities. They can either be included in the contract plans or given to the resident engineer for his use in field staking and construction.

It is also desirable to plot sample cross-sections throughout the project at intervals varying from 200 to 1,000 ft depending on the terrain. These generally include one section in each cut and fill and any others which are necessary to show unusual conditions such as sliver cuts and fills, benches, special ditches, channel changes, etc. They are of use to the designer in studying the project as well as to field engineers in staking and construction. As the construction contractors will also be interested in such information for bidding purposes, the sample cross-sections are included in the contract plans. Since they are used for pictorial purposes only, the scale can be as small as 1 in. = 20 f or more horizontally, and to whatever vertical scale will best fit the individual project. The use of small-scale illustrative cross-sections has effected a material reduction in the volume of contract plans.

Results Obtained

There is no longer any doubt that photogrammetric maps such as these are sufficiently accurate for the computation of preliminary earthwork quantities. Present practice is to cross-section again immediately prior to construction for determination of final pay quantities. On several projects a comparison of preliminary quantities from photogrammetric maps and final quantities from field cross-sections shows a difference of less than 1 percent. Very few projects have been reported where the difference was greater than 2½ percent.

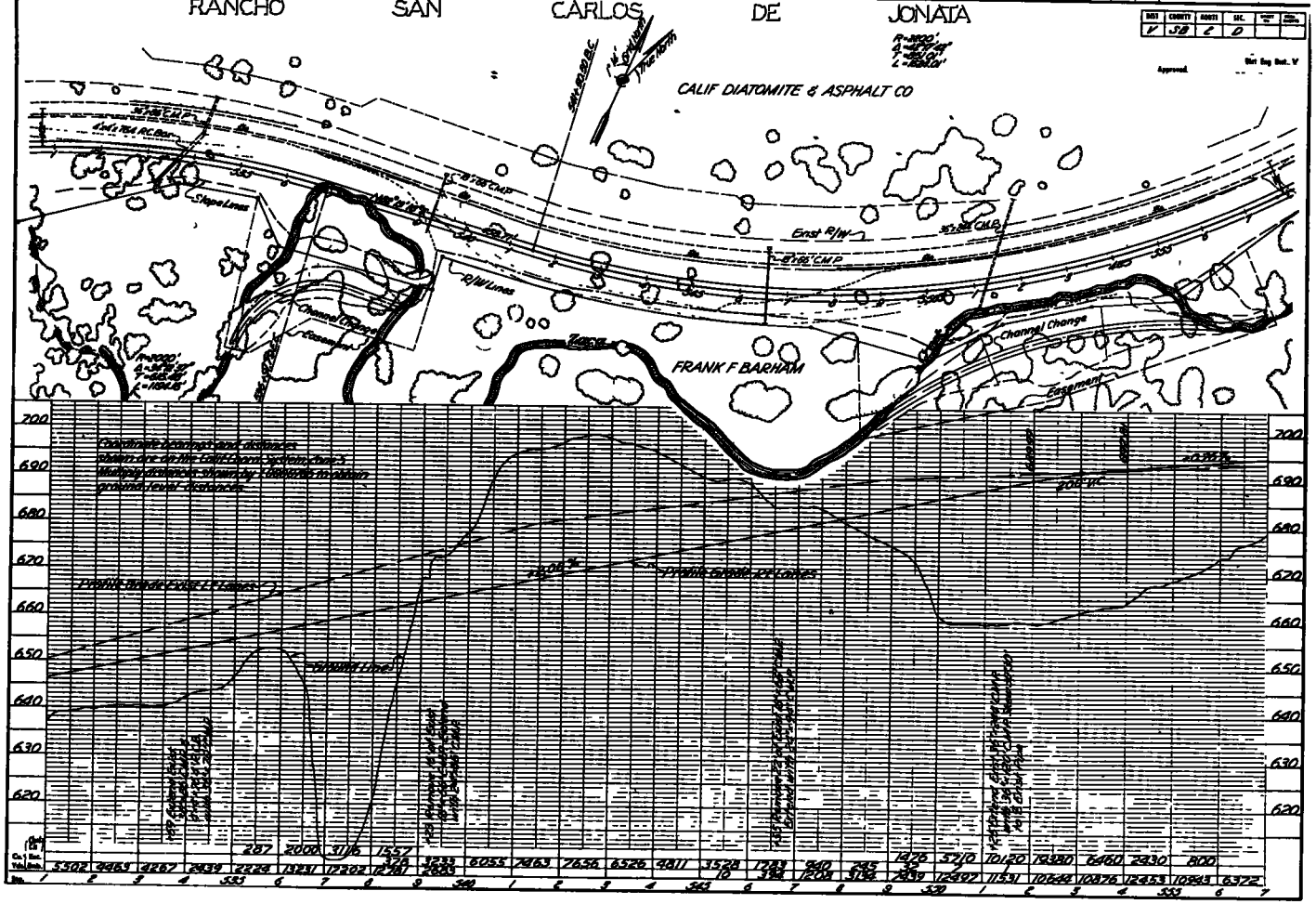

Figure 8. A sheet of completed contract plans has been developed from the photogrammetric mapping illustrated by Figure 7. Earthwork quantities obtained by machine computation are shown at the bottom of the sheet.

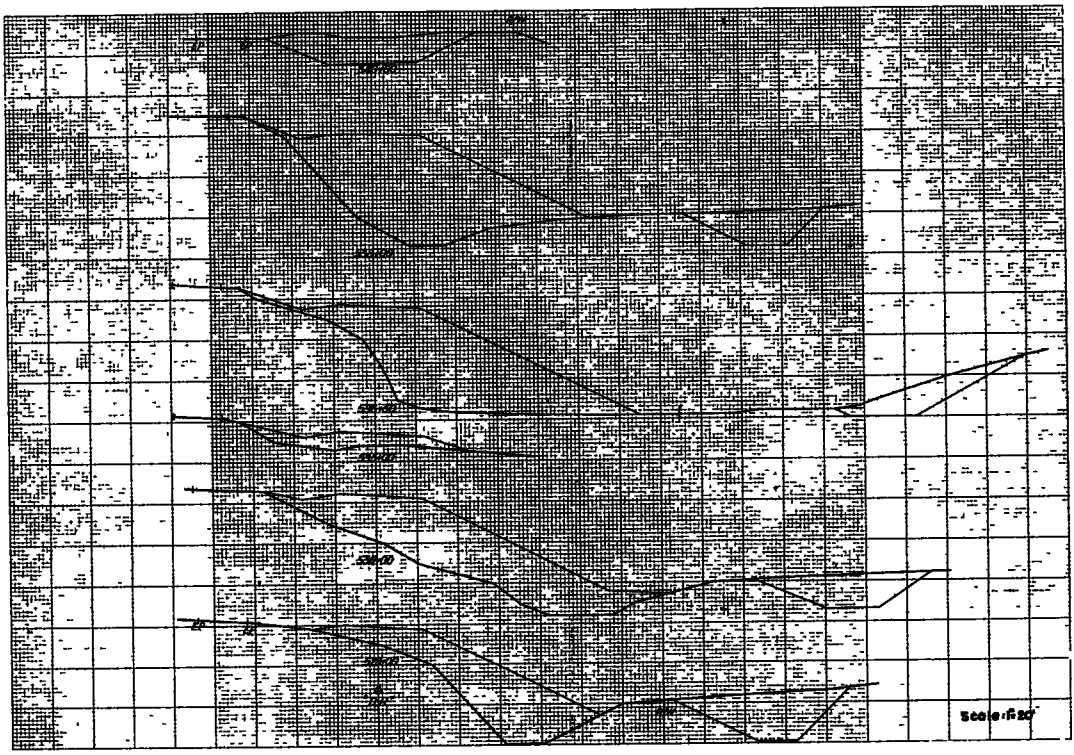

Figure 9. Small-scale pictorial cross-sections are useful to the designer, the construction engineer, and the contractor.

The actual savings effected by the use of design mapping are much easier to measure than those obtained from the use of aerial photos or reconnaissance mapping. Data reported by several districts indicate a saving of 40 percent is cost and 70 to 80 percent in manpower as compared to conventional field survey methods. A further saving of between 30 and 50 percent is achieved in design when photogrammetric mapping and electronic computers are used.

The use of large-scale photogrammetric mapping has been rapidly increasing during the past five years and is now generally accepted as standard practice for the design of freeways in California. At the present time the Division of Highways has 33 contracts for design mapping under way. These contracts provide for mapping a total of 376 miles at a cost of $560,000. Construction costs of the highway projects covered by this mapping are estimated at over 190 million dollars.