Hungry Horse Dam, the principal feature of the Hungry Horse Project, is located on the South Fork of the Flathead River in northwestern Montana near Glacier National Park. The dam is located approximately 3 miles from Hungry Horse, 9 miles southeast of Columbia Falls and 17 air miles northeast of Kalispell, Montana, in the Flathead National Forest (see Figure 1).

Hungry Horse Dam is a variable thickness, concrete arch-type structure constructed between 1948 and 1953. The dam has a crest length of 2,115 feet, a structural height of 564 feet and a hydraulic height of 515 feet. The crest has a thickness of 35 feet at elevation 3565.0 feet, and a maximum base thickness of approximately 320 feet. The dam contains 2,934,321 yd³ of concrete.

The spillway is located at the right abutment and consists of a morning glory-type inlet structure surmounted by a ring gate with a diameter of 64 feet and a crest elevation of 3560.0 feet and a maximum base thickness of approximately 320 feet. The dam contains 2,934,321 yd³ of concrete.

The power plant, located at the downstream toe of the dam, includes four 162-inch-diameter penstocks that supply four 105,000-horsepower Francis-type turbines. The total generating capacity of the plant is 428,000 kilowatts. Figure 2 shows a general layout of Hungry Horse Dam and Power Plant.

Hungry Horse Reservoir provides storage for power generation, flood control, irrigation, and recreation. The dam forms a reservoir approximately 34 miles long, with a maximum width of 3 ½ miles. Reservoir capacity is nearly 3.5 million acre-feet. The maximum depth of the reservoir is 500 feet.
in documenting geologic features on the abutments. The decision was made to attempt to use historic photography of the Hungry Horse Dam to collect geologic and topographic data from the abutments shown in the images for an initial phase of the exploration program.

GEOLOGY

Regional Geology

Hungry Horse Dam is located in an area of high mountains and ridges made up of sedimentary rocks described as the belt series of the Proterozoic Era, Precambrian. The valley areas are covered with geologically younger Tertiary age lakebed deposits, Pleistocene glacial deposits, and Holocene alluvial deposits.

In the general vicinity of the damsite are three formations of the belt series. The Grinnel Formation is the oldest and consists of thinly laminated to massive argillite containing some quartzite beds. Overlying the Grinnel argillite is the younger Siyeh Formation that consists of siliceous, argillaceous, and dolomitic limestone. Hungry Horse Dam is located within this formation. The third and uppermost formation is the Missoula Formation composed of thinly bedded argillites and quartzites.

Site Geology

The Siyeh Limestone Formation underlies both abutments and the toe area of the dam. Bedding in the Siyeh is generally regular and is shown by a difference of mineral composition, color and texture. The beds range in thickness from a few inches to several feet, are continuous and composed of fine grained material of medium hardness, bluish gray to greenish gray in color with some light gray beds. Nowhere is the limestone pure, instead varying amounts of siliceous, argillaceous and dolomitic materials are present. These impurities in the limestone have slightly increased the hardness of the rock and have increased the resistance of the rock to erosion and weathering over that of a pure limestone. The siliceous beds are light gray, the argillaceous beds are greenish gray and the beds high in calcareous material are bluish gray in color.

At the damsite the bedding has an average strike and dip of N38° W, 30° NE. The slope of the left abutment has been controlled by the dip of the bedding, while the slope of the right abutment has been controlled by the northwest striking joints.

PHOTOGRAHMETRIC ANALYSIS

Gary Robertson & Assoc. Inc. (GRAI) was contracted to perform the necessary photogrammetric studies, including collection of accurate coordinate data from historic black and white photography for the purpose of depicting, mapping and analyzing, three-dimensional geologic and topographic features.

For inaccessible areas, close range photogrammetry provides the best means for providing orientation and extent of discontinuities. For the photogrammetric analysis images had to be obtained showing the exposed slopes mainly the downstream portion of the dam abutments. The site was under heavy tree cover Figures 3,4,5,6 will illustrate the difference found in historic images versus the 1997 photography. After the review of the construction progress photos, seven historic images were selected which offered the best coverage of the slopes.
The basic problems with the images were:

1. Photos were taken during different time periods during the construction process.
2. No information available on camera type and focal length.
3. No negatives of the selected images were available.

Natural points or features had to be identified and checked to see if they were visible in the historic imagery, fortunately there was areas that were visible. During the field survey work supplementary photo images or an extant record was taken of the left and right abutment with a Rollei Camera.

The selected photographic prints were scanned and a test was made to determine the film format and the camera focal length. We determined that the film format was 4"x5" (inch). The focal length used for the historic images were 90.6 and 135mm. Image coordinates were acquired and computed through a self-calibration bundle solution. The output showed a RMS value of $X = 0.186$, $Y = 0.304$ and $Z = 0.258$ (feet) well within the specified accuracy objective.

DATA REDUCTION

Geologist had determined previously the fault lines, bedding planes, and areas of discontinuities were orientation information was required. For trend surfaces we normally read a minimum of five coordinate points per plane to allow for a test of correlation factors.

Coordinate data along the fault lines and bedding planes posed some problems. The problems were the orientation of photo images, lighting and variation of camera heights and orientation, which posed a problem with acquiring coordinate data. Image processing techniques such as pattern and line matching was used. In addition coordinate string data was determined using forward – backward transformation to locate the position of the image coordinate data. Figure 7,8,9.
blocks in the abutment that may have potential failure planes. Once these blocks are identified and failure planes analyzed, the risk potential at Hungry Horse Dam may be reduced. However, analysis is still ongoing and no official results are available.

REFERENCES


Robertson, G., A. MacRae, 1982, "Use of Photogrammetric Methods for Mine Slope Deformation Surveys" presented paper, Fourth Canadian Symposium on Mining Survey and Deformation Measurements, Banff, Alberta, Canada.

Robertson, G., 1984 "Application of Photogrammetry in Mining and Geotechnical Engineering" presented paper ASPRS workshop on state of the art close range photogrammetry, San Antonio, Texas, USA

Robertson, G., 1991 “Monitoring Static and Dynamic Movements of Geotechnical Features by Close Range Photogrammetry” presented paper First Australian Photogrammetric Conference Sydney, Australia


CONCLUSION

The data from the photogrammetric studies performed by GRAI will be used to re-analyze the potential risks associated with seismic (dynamic) and static loading conditions at Hungry Horse Dam. Currently, strike and dips of joint data generated by the photogrammetric studies are being compared to archival data for joint set matches. These joint sets will then be used to delineate

<table>
<thead>
<tr>
<th>Set</th>
<th>GRAI DATA</th>
<th>APO DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N76E 72SE</td>
<td>N75E 873SE</td>
</tr>
<tr>
<td>2</td>
<td>N52W 44SW</td>
<td>N46W 40SW</td>
</tr>
<tr>
<td>3</td>
<td>N73E 69SE</td>
<td>N67E 68SE</td>
</tr>
<tr>
<td>4</td>
<td>N56W 61SW</td>
<td>N55W 61SW</td>
</tr>
<tr>
<td>5</td>
<td>N23 57SW</td>
<td>N22W 59SW</td>
</tr>
<tr>
<td>6</td>
<td>N46E 21SE</td>
<td>NAPCF</td>
</tr>
<tr>
<td>7</td>
<td>N20W 37SW</td>
<td>N75E 89SE</td>
</tr>
<tr>
<td>8</td>
<td>N41W 20SW</td>
<td>NAPCF</td>
</tr>
<tr>
<td>9</td>
<td>N38W 43SW</td>
<td>N29W 59SW</td>
</tr>
<tr>
<td>10</td>
<td>N38W 43SW</td>
<td>N53W 82NE</td>
</tr>
<tr>
<td>11</td>
<td>N61E 55SE</td>
<td>NAPCF</td>
</tr>
<tr>
<td>12</td>
<td>N7E 81NW</td>
<td>N6E 81NW</td>
</tr>
</tbody>
</table>

Table I

Dip and Strike

Figure 10 Location of Data Sets

For the trend data surface or orientation computation GRAI uses a series of x,y,z coordinates the routine is in fact a multiple regression analysis in the form of 
\[ z = b(1) + b(2)x + b(3)y \] since x and y are considered to be accurate and only z shows some variance the calculation of r the correlation coefficient. We have tried previously treating the three variables as entirely independent but mainly use the above technique. The Bureau of Reclamation used a technique of selecting 3-point data sorting using all the point combinations with no data smoothing. The following is a comparison of the two methods in regard to the right Dam abutment. (Table 1) A Strike is the azimuth of a horizontal line on the discontinuity while Dip is the maximum angle the discontinuity makes with the horizontal. The coordinate data is taken on a plane and the software does not make any adjustments for waviness.

CONCLUSION