Micro-Hydro: Civil Engineering Aspects

by: D. Mansell, G. Atkins, and S. Kiek

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by D.S. Mansell, G.P. Atkins, S.N. Kiek

(Civil Engineering Department,
Papua New Guinea University of Technology)

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SYNOPSIS:

The paper sets out to identify some of the aspects of small hydro-electric schemes which are of particular concern to the civil engineer, and to provide some guidance to non-engineers who wish to build such power sources.

1. INTRODUCTION

While an electric supply is indisputibly an important aid to development there are problems of all kinds involved in establishing a supply to a rural population. These include cultural problems which could occur if a power-scheme were wished onto a community without a sense of proprietorship and responsibility being developed first, or which could occur if creation of the supply were not associated with education in its potential usefulness. In addition, there are electrical problems of transmission and reticulation of the electricity, and mechanical problems with governing of generators and maintenance of appliances.

But in the case of hydro-power there are also serious problems of a civil engineering nature in the construction of a scheme and in maintaining it. Attention is therefore directed in this paper to that type of scheme which is likely to be built as a private or semi-private venture with a minimum of professional engineering input. These are schemes with turbines rated up to about 200 kW which are attractive to schools, missions and small commercial enterprises. They are commonly referred to as "micro-hydro".

With the high price of fuel for internal combustion engines, and the sophisticated maintenance skills they require, hydro-power is naturally seen as a valuable, self-replenishing, indigenous alternative source of energy suitable for rural development. However, small schemes are viable only under certain circumstances because of their high capital cost and relatively inflexible control over output. They are economical only if compact. The hydraulic source of energy must be close to the point of consumption because of the cost of transporting water and the cost of transmitting electricity.

The first of these costs constitutes the civil engineering aspect of micro-hydro. There is little value in discussion of costs themselves since there is no sound basis for extrapolation of costs from one scheme to another. Discussion is restricted to some of the facts, problems and ideas which may be of interest to a person wishing to investigate the feasibility of a small scheme.

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2. HYDROLOGY CONSIDERATIONS FOR MICRO-HYDRO

2.1 Low Flows

There are micro-hydro schemes operating unsatisfactorily in Papua New Guinea because the low flows have been badly estimated, or not estimated at all. To ensure a continuous supply of electricity, the low flow of a stream must be sufficient to operate the turbine. When this is overlooked - and it has been in some installations in Papua New Guinea - the hydro plant becomes inoperable in the dry season in some years, or perhaps even every year.

There may be records available from a hydrometric station on the stream. These records may be obtained from the Bureau of Water Resources, which is part of the Office of Minerals and Energy in Konedobu.

In most cases, records are not available for small streams and so measurements of stream flow must be made. These must be made at a time of low flow. An appropriate procedure is as follows:

a) Choose a reasonably straight section of stream of 100 metres length
b) Measure the width and the average depth of the water at about five locations in the straight section. The average depth at each location can be determined by measuring the depth at about ten equidistant points across the stream and averaging the ten depths.
c) For each of the five locations along the stream calculate the cross-sectional area of flow by

$$A = W \times D$$

where W = width of stream (metres)
D = average of ten depths (metres)
A = area (square metres)

d) Calculate the average of the five areas.
e) Using a piece of wood and a watch determine the surface velocity (V_s) of the stream. This is done by floating the piece of wood down the middle of the stream and timing it over the 100 metres. This should be done about ten times and the average value calculated. The piece of wood should be more substantial than a matchstick and should be submerged by one to two centimetres.
f) Calculate the average velocity (Vave) of the stream by

$$Vave = 0.9 \times V_s$$

where V_s = surface velocity (metres/sec)
Vave = average velocity (metres/sec)

g) Calculate the flow rate (Q) by

$$Q = V_{ave} \times A$$

where Q = flow rate (cubic metres/sec)

The design low flow must now be estimated on the basis of "local knowledge" of how low the stream is in a dry year. A reasonable approximation is that

$$Q \text{ is proportional to } d^3$$

where d = depth of water taking the lowest point on the stream bed as the datum.

so that $Q_D = Q \times \left(\frac{d_L}{d}\right)^3$

where d_L = depth from "local knowledge"
d = measured depth
Q_D = design low flow.

Thus, if it is known that the depth may be expected to be as low as one half of the depth measured (i.e. $\frac{d_L}{d} = \frac{1}{2}$), the design low flow is $Q_D = Q \times \left(\frac{1}{2}\right)^3 = \frac{Q}{8}$

Sometimes a reasonably straight length of stream of 100 metres is not available. The above procedure can be carried out satisfactorily on a section of stream as short as 10 metres. Even if the stream is in cascades, volume measurements using buckets etc can be carried out.

2.2 Flood Flows

The intake structures from the stream must be protected from flood flows. Flood flows can be estimated using the procedures described in "Flood Estimation Manual". Copies are available from the Department of Public Works.

3. STRUCTURAL PROBLEMS IN SMALL SCHEMES

3.1 Why Build Structures?

In order to reduce costs to a minimum it is desirable to avoid structures as far as possible. A "run of the river" scheme saves the cost of an expensive storage dam, but provides no moderation of the variabilities of stream flow. An earthen flume will usually be cheaper than a built one, and involves skill only on the part of the supervisor, since apart from fairly accurate levelling to an appropriate grade it involves only labouring work. However there are occasions when a structural flume is required. The natural soil may be so pervious that a small source of water is wasted through excessive loss between the stream and the penstock. Or it may be so hard that excavation involves skills or equipment which are unavailable. In tortuous terrain it may be economical to use structures to short-circuit sharp gullies instead of following a long contour deviation from one spur to the adjacent one. Earthen flumes may also be impractical if they are near the bottom of a steep forested slope in very wet country because of the management problems created by debris and soil washed into them from the slope above. And lastly a slope which is already near the limit of stability may become unmanageable if excavated for a flume.

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3.2 Materials for Structures

Flumes have been constructed for many years from *timber*. This technique has been common in mining areas, using local materials, and requiring only common tools and skills. There is no need to describe these in detail, since examples are still available for inspection in Papua New Guinea.

It is desirable to keep timber flume up off the ground in order to reduce the rate at which it deteriorates. The timber should be treated with preservative and should be used in thicknesses of not less than 30 mm, if it carried load except in the case of ply.

Since timber continues to sag for long periods after it is loaded, supports should be close together.

The details of a timber flume design depend on the type of timber and skills available and on the required size of the flume. *Round Poles* or *sawn timber* can be used to make quite strong trusses or girders spanning several metres and can support a light water-retaining lining of thinner planks or *plywood*. If the required size of flume is estimated from its hydraulic characteristics and the relative costs of materials are obtained, the flume can be designed to achieve the most economical arrangement.

Steel or concrete pipes have the advantage that, being closed, they need not follow a grade line. Unfortunately they must be purchased and transported from an industrial centre which makes them very expensive. However the most economical structural solution to a flume may involve a closed conduit over part of its length when the terrain demands it.

Proprietory lines of semi-circular cross-section steel conduit are more compact to transport and therefore are more competitive than complete pipes. They are generally used as open channels or flumes following the specified grade line.

Concrete is a relatively impervious material, which is made mostly from locally available materials. Only the cement need be purchased. Its durability is usually better than that of other materials. It may therefore be continuously supported by the ground for the entire length of the flume if other conditions are suitable. If it must be supported above the ground, it is strong enough to carry its own weight and the water over quite large spans, as long as it is reinforced with steel.

It is also possible to use concrete for durable supports (piers) and for the main load-bearing beams, and to use thinner concrete or timber planks to retain the water.

However it is difficult to make concrete products of reliable quality in thin sections, and heavier sections pose problems in handling if they are precast. If they are cast "in-situ" (i.e. in place) formwork costs may become excessive. Thus we have the situation in Papua New Guinea where some hydro-scheme owners wish to use concrete because of its durability, who would be better able to handle structures made from timber because of its lightness and the familiarity of methods of working it.

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The minimum practicable thickness of concrete depends on the coarsest size of stone used in the mix, on the largest size of steel reinforcing bar, and on the thickness of concrete "cover" to protect the steel from corrosion. If light structural steel fabric (mesh) is used for reinforcement and the largest size of stone particle is approximately 10mm the thinnest practicable concrete element is about 50mm and thicknesses of at least 75mm are more realistic.

In micro-hydro it is wise to resist the temptation to use unreinforced concrete.

If a sound concrete with adequate strength for use as a structural load-bearing material is required the most important feature of the mix is the ratio of the weight of water to the weight of cement. A low ratio (dry mix) gives high strength if the mix can be thoroughly mixed and adequately compacted. A high ratio (wet mix) gives easy mixing and compaction but low strength. For manual methods of mixing and compaction, a ratio of about 60% is near the optimum (i.e. about 0.6 litres of water per kilogram of cement). The sand and stone makes the concrete more economical and may be important in determining the strength. The ratio by mass of cement to fine and to coarse aggregate should be 1:2:4. Fine aggregate (sand) is able to pass through a 3/16" (4,76mm) sieve. Coarse aggregate (stone) is unable to pass this sieve. In Papua New Guinea it is sometimes impossible to obtain fine and coarse aggregate separately and a complete river gravel is used. In this situation the ratio by mass of cement to total aggregate should be 1:6.

It is preferable to use washed aggregates, in order to remove clay, silt and organic matter which are harmful to concrete for various reasons. It would usually be a justified precaution to send a large plastic bag of the sand stone or gravel to the Public Works Department or to the Civil Engineering Department of the University of Technology for testing before undertaking a large volume of concreting. The costs incurred are much less than the cost of the cement used in a micro-hydro scheme with structural components and are a justified precautionary expense.

The weight of water calculated to be required includes the water retained in the sand and stone before mixing. Since it is difficult to measure the amount of water held in the interstices of aggregates unless one has access to accurate balances it is wise to cover the aggregate during rain. However, if this is also impossible it is necessary to judge the correct amount of added water by visual assessment of the concrete as it mixed. It may be helpful to start by drying some of the materials and carefully weigh-batching them (i.e. mix in carefully weighed quantities). The appearance and behaviour of the mix is then memorised as a guide to subsequent control of quanlity. An aid to memory for this purpose is the way the mix retains a vertical surface when pushed with a trowel, or the depth of an impression created by placing a weight on a thick layer of the freshly mixed concrete.

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Water retaining elements may be formed from *butyl rubber* which is available in long rolls which can be easily jointed. A range of thicknesses and types is available and is claimed to be resistant to damage from ultra-violet radiation. This material is in common use in industrial and municipal water storage. It is comparable in price with materials such as plywood, but is more easily transported. The main disadvantage is that it must be adequately supported, and the cost of the supporting medium may make rubber uneconomical in many applications.

However it would be interesting to experiment with a steel mesh trough supporting a rubber liner. The hydraulic characteristics of this are not known but should be acceptable, and the components of the flume would be light, easily transported, and easily assembled. An illustration of such a flume is shown in Figure 1.

The risk of damage by vandals should be assessed individually for each application, and would depend on the involvement of the local people in the project.

3.3 Form for Structures

A flume may have any cross-section, but semi-circular, rectangular, and trapezoidal shapes are common and their hydraulic properties are well-known. The choice of shape may be dictated by the method of construction or the materials used. Once this is determined, the water-carrying capacity for a given slope and given surface texture can be predicted by an engineer.

3.4 Other Structural Problems

Other important structures in micro-hydro schemes are stilling basins, weirs and dams and power-houses. These will not be discussed in this paper, except for the comment that in many instances an otherwise satisfactory stilling basin or weir is made unmanageable or unusable by the failure to provide for removal of silt. Structures of this kind, by their very nature, reduce the velocity of water and therefore allow it to deposit part of its load of silt and grit. Therefore off-takes should be well above the bottom, and a special off-take leading straight down-stream to the river should be provided at the lowest point for removal of silt. It needs a gate which can be operated with the full weight of water and silt against it. If operated regularly (which is more likely to happen if it is operated easily) it will prevent the necessity to close the scheme down.

An alternative is to provide a by-pass so that the scheme can operate without the silted-up structure long enough for it to be cleaned out.

4. HYDRAULIC CHARACTERISTICS OF FLUMES, PENSTOCKS AND TURBINES.

The flume is used to convey the water from its source or its diversion to the reservoir or stilling basin at the top of the pressure pipe (penstock) which delivers it to the turbine at high pressure. The penstock must be a closed conduit so that the water can build up pressure as it falls to the turbine.

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The water velocity is normally high and some of its energy is lost in friction. The bigger the penstock the lower the velocity, and the smaller the lost energy. Therefore developers of small hydro-schemes are in danger of choosing small pipes for small schemes, in the pursuit of economy, and subsequently discovering that the power output is disappointing. A 75mm to 100mm diameter pipe should be considered the minimum practical size and even then should be used for only very small turbines. Diameters of 200 to 300mm will normally be more economical.

Similarly the length of the penstock should be as short as possible in order to minimise friction loss quite apart from capital savings.

A preliminary estimate of the output of a scheme may be obtained by assuming the net available "head" is about 70% of the difference in height between the stilling basin or reservoir at the top of the penstock and the level of the tailwater (or the bottom of the turbine draft-tube whichever is higher). If this net head is measured in metres and the amount of water available is estimated in cubic metres (1000 litres) per second, the estimated power output in kilowatts is obtained by multiplying the product by 7.

Thus a net head of 25 metres, and a flow of 1/2 cubic metre per second ("cumec") will produce about 2 5 x ½ x 7 = 88 kW.

To obtain a more reliable estimate, the size and length of the penstock and the choice of material from which it is made should be given to an engineer, together with the total head and the available water discharge.

Alternatively having determined the design low flow (as described in paragraph 2.1) and knowing the power output required, then the required "head" can be determined. This determines the site chosen and the type and size of turbine chosen. A pelton wheel is suitable for heads greater than say 200 metres. Francis turbines are suitable for heads of 30 metres to 450 metres and propellor turbines are suitable for heads up to 40 metres.

5. SOIL PROBLEMS IN SMALL EARTH DAMS

5.1 Why Earth Dams?

Earth dams are commonly used in small scale works even though the substantial economies which make them such a good proposition in large dams cannot be gained. These have been the result of the improvement of earth moving machinery and methods of controlling the placement of earthfill. Whilst it is impossible to obtain large scale equipment for small jobs in remote areas, it is still often easier and cheaper to use earthfill than concrete which requires the transport of cement to the site and, probably, reinforcement, despite the restriction of equipment to that which is comparatively unsophisticated.

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5.2 Dangers in Earth Dams on Small Scale

As just mentioned, one of the reasons for the overwhelming success of earth dams on a large scale, apart from the use of large scale equipment, has been improved methods of controlling placement of the material in the embankment. Unfortunately, whilst it is possible to achieve success with inferior equipment it is not possible with inferior methods of control other than to a limited extent. There is considerable danger of failure if matters are left to chance as they, nevertheless, usually are. The usual attitude is that, rather than go to the bother of achieving adequate technical control, it is better to risk failure. Provided that this risk is knowingly faced, this attitude may have merits as many dams have been constructed without any special attention to control of placement and have remained standing. Proper control will ensure success but will cost some effort.

5.3 What can be Learnt from Major Dams

In major earth dam construction, the soil to be used is selected after an exhaustive investigation of all the available deposits of earth materials within reasonable haul distance of the site. Their properties are determined in laboratory investigations and are thus known with some degree of accuracy. A design is then made which takes account of these properties. The placement of the material is then controlled to ensure that the soil in place has the design properties by sampling and testing on site. Whilst we cannot do all this in its entirety for minor earth dams, we can learn much from it. Usually our selection of materials is very limited owing to limited facilities for transporting the soil over any considerable distance. We may, therefore, have to accept material of inferior quality. However, we can have the material tested in a soils laboratory (such as that at the University of Technology) to discover exactly what those properties are. Even quite a small job will probably find that expense supportable. We will not be able to spend much time and money on elaborate design procedures and will probably decide quite arbitrarily that all we can afford to do is to make an embankment of only one material - impervious earthfill - in lieu of the multizone designs which characterise major structures. We can, nevertheless, easily determine if the strength of the dam will be adequate if the material is placed as determined in the laboratory as being able to produce the best results. Although we cannot go to the expense of establishing a control laboratory on the site and a system of inspection and testing as is so very economic in major works, we can check with simple field tests that the material was placed in accordance with the results of the laboratory determinations.

5.4 Properties to be Measured

a) Field Density: When the material has been selected some estimate of quantity is necessary to know if there is sufficient soil in the deposit. If at all possible, this will be a better informed guess if we know the field density. The soil will need to be much denser in the dam than it is in the deposit. Thus any rough survey of the deposit from which the quantity of soil can be calculated will not, of itself, tell us if it will be sufficient when compacted in the dam. Field density can be measured using the traditional sand replacement method. A small hole is made and filled with standard sand from the laboratory whose density is known. The soil excavated is weighed and its moisture content found in the laboratory. The volume of the hole is known from the amount of sand it required to fill it. The density is then calculated.

b) Compaction:

About 25 kg of soil should be taken from the deposit and sent to the laboratory for a compaction test. This should be sent in a plastic bag not a hessian sack from which fine particles can escape. The compaction test will determine the maximum density (and therefore strongest condition) which the available rolling equipment is likely to be able to achieve. It will also tell us the best moisture content for rolling.

c) Yield:

We now know how great a volume of soil we must have in the deposit to build our dam because we can determine its "yield" i.e. the percentage the volume of the soil in the dam is of that in the deposit, i.e. $\frac{100 \times \text{field density}}{\text{compacted density}}$.

d) Shear Strength:

To be sure our earthfill dam, even at its maximum density, will be strong enough to stand up with the slopes we have guessed as safe, we need to know its shear strength. If it is a pure clay this may be determined in the field very cheaply although it is probably better in the laboratory. Some technical help will then be needed to interpret the result in terms of the stability of the dam. Any soils engineer or even a final year student can help. If the dam will not have adequate strength the slopes must be flattened until it will.

e) Construction Control:

We now know that if we can roll our earthfill material until it has the density determined in the compaction test, it should have sufficient strength. In order to make rolling easier it is necessary to have the soil as close as possible to the 'optimum moisture content' found in the compaction test. There will be no time to dry a sample of the soil during construction to ensure that this is so. Pour a little methylated spirit on a weighed sample of the moist soil and burn it and weigh again. Thus calculate the moisture content. If it is too wet, allow it to dry out before further rolling. If it is too dry, add water preferably on the embankment immediately before rolling. We must also check the field density to ensure that we do actually achieve the density from the compaction test. This will tell us whether further rolling is required and when to stop rolling.

f) Thickness of Courses:

How much earthfill should be added at once for each rolling? This depends on the kind of rolling equipment. If a flat cylindrical roller is being used, it will not compact more than about 5cm. With a rubber tyred roller about 15cm can be compacted at once. Truck tyres will compact about 10cm to 15cm depending on the load on the truck and its weight. Very heavy rubber tyred rollers will compact more. However, for the type of material which will make a good dam i.e. an impervious clayey material, a sheeps foot roller is best if we are fortunate enough to get one. It will compact a layer to the depth of its feet.

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5.5 Spillway

It is hardly necessary to point out that no earth dam however well constructed and however much control is exercised, will remain standing if it becomes overtopped in a flood. To ensure this will not happen it is necessary to find (from records if possible) the maximum flood likely to occur in the water course being dammed. It is then necessary to find a spillway site to build a concrete or rock spillway over which this flood could pass. The bottom of the spillway must be at full supply level in the dam and the dam must be higher than this by an amount (called "freeboard") which will allow the maximum flood to pass over the spillway without overtopping the dams. The advice of an hydraulics engineer will be needed for this. The spillway site need not be immediately beside the dam. It is often possible to avoid an expensive concrete structure where a cutting may be made with, perhaps, a natural rock bottom for a spillway. It may even be possible to use the material excavated in the dam.

6. CONCLUSION

6.1 The cost of transporting water is a factor which may make a small hydro-scheme infeasible. It is often best economy to use earthen flumes, but features of terrain and climate may make this impracticable.

6.2 There is a variety of types of flume and of materials, the choice of which requires knowledge of local materials.

6.3 Penstocks should be short and not too narrow.

6.4 Testing of soils for dams and of aggregates for concrete is a worthwhile investigatory precaution, and can be carried out in this country.

6.5 It is possible to build small dams with reasonable certainty of success with the use of a little simple technology. Such dams should not exceed 5 metres in height.

6.6 Some rules of thumb are included in the paper to help initial appraisal and planning of potential micro-hydro schemes.

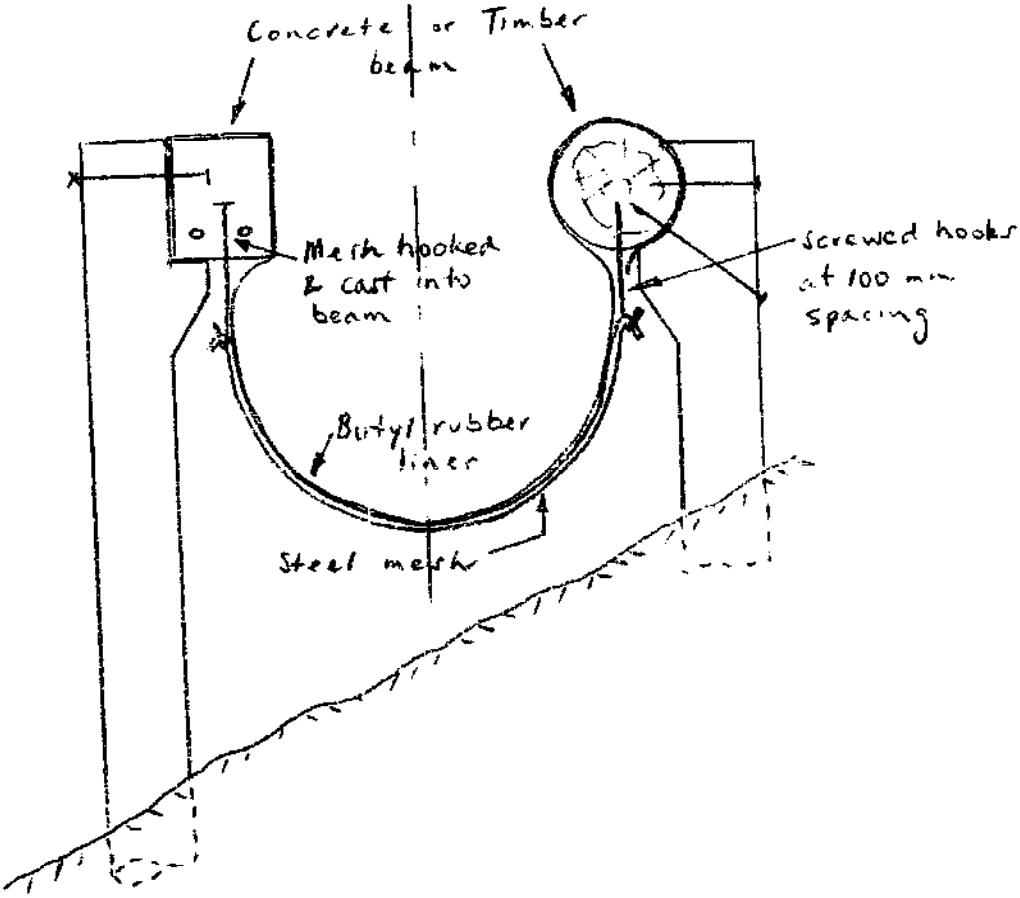
Concrete or Timber beam
Mesh hooked & cast into beam
screwed hooks at 100 mm spacing
Butyl rubber liner
Steel mesh

FIG. 1