DESIGN OF POWER EXCAVATORS.

PAPER

MECHANICAL AND ELECTRICAL DESIGN OF POWER EXCAVATORS.

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JUSTIFICATION FOR USE OF POWER EXCAVATORS.

The power excavator owes its original existence, and subsequent widespread use, to the fairly obvious fact that the great and small earth and mineral moving projects of the world could never be carried out economically by manual labour, even if such labour were available in ample quantity. Irrigation and reclamation works, construction of railways, docks, harbours, etc., open-strip mineral mining, quarry working, as well as large and small contracting works have been rendered possible to their present extent only by the power excavator.

HISTORY OF POWER EXCAVATION.

The detailed history of power excavators is material for several volumes, and it is therefore proposed to refer to this history only in such a way as to give a sound general impression of the course of development.

Prior to 1836 a very crude single steam engined digger was produced by one Otis, of Philadelphia, U.S.A., for work on the first American railroad construction between Albany and Schenectady, in N.Y. State. This machine, although crude, clumsy and slow, quite justified its existence and did considerable excavation at much lower cost than equivalent hand labour.

Between this time and about 1875 several steam excavators were built in America, and, it is believed, one or two were tried in Europe with very indifferent success. The American-built machines, about twelve in number, all did fair work on the Erie Canal and other jobs, but, owing to the high-handed attitude of the manufacturers, few customers were obtained or retained. Moreover, during this period unrestricted immigration to the "New World" resulted in a supply of low-paid, rough labour, approximately sufficient for the needs of development at that time.

Towards the end of the "Seventies" development of the U.S.A. began to grow rapidly beyond the capacity of the supply of hand labour, and shortly after that time began the true development of the power excavator as we know it today.
Considerable, and occasionally acrimonious, argument has occurred from time to time as to who got going first. There is really very little in it, and, therefore, so as to hurt no feelings and still retain individual dignity, it might be fairly said that the Marion and Bucyrus Companies got going at about the same time in the early "Eighties." In England, too, something of a start was made about the same time with a fairly crude digger called, for many years, the steam navvy, but bearing very little resemblance to the machines of the present day.

The Railroad Type Excavator held the field for many years. This type, an illustration of which will be shown, was really a very strong steel railroad bogie car having mounted upon it a boiler and steam hauling mechanism, and having a jib and dipper handle with bucket. This jib equipment had a bull wheel or rotating base capable of being swung by wire rope or chain drive to either side of the machine through an angle of slightly more than 180 degrees so as to be able to load into waggons on either side. The dipper handle thrusting motion was obtained by so reaving the hoist rope or chain as to obtain forward or backward movement as required, but not without also actuating the hoist a corresponding amount. This was long before the days of the separate crowding or thrusting engine mounted on the jib and operating the racking in and out of the digger arm.

Following upon this came the small capacity full revolving excavator mounted on rail or road wheels. This machine was also originally single engined, transmitted its power and movement through a fairly complicated train of gears, clutches and frictions. The whole upper works and jib was free to revolve as required around a king post pivot, the lower traction equipment, of course, remaining stationary.

This brings us somewhere to about the beginning of the present century, at which time there began to develop several schools of thought as to what was and was not first class practice, and the ever-widening controversy leads us to the multiplicity of designs on the market to-day, good, bad and indifferent.

In the early part of this century the three-engines, full-revolving steam excavator was produced, and the first class makers all agreed that the principle of having a separate engine for each motion (hoist, swing and crowd) was undoubtedly the right way to go about it, inasmuch as much complicated transmission gear was automatically eliminated, moving parts were reduced to a minimum, higher working speeds were obtained, and a more elastic machine in every way was the result.
(It might here be mentioned that this agreement is quite in line with the general tendency which began about this time, whereby all engineers tended more and more towards "separate motors" for each driven machine in general engineering practice.)

Developments came thick and fast between 1910 and the present day, notable landmarks being:

(a) The internal-combustion single-engined friction machine.
(b) The single motor electric excavator.
(c) The two-motor electric excavator.
(d) The large revolving excavator.
(e) The three-motor electric D.C. machine.
(g) The internal-combustion-electric machine.

GENERAL DESCRIPTION OF EXCAVATOR FUNCTIONS.

Before going on to describe the main characteristics of the various machines above enumerated, it is proposed, for the benefit of those who happen to know very little about excavators, to explain the functions of the various main types.

Shovel.—In a power shovel one has a rigid jib or boom, a rigid digger arm working round or through the jib, and having rigidly fixed to its business end a suitable bucket with digging teeth. The bucket normally is put at the work with teeth horizontal, and the open side of the bucket facing the material to be attacked. The hoisting mechanism then commences to hoist the bucket radially upwards, whilst the thrusting mechanism is caused to push the bucket outwards into the material, the combined motions causing the digging of the ground and the filling of the bucket. The whole machine is then swung mechanically, with full bucket on extended arm, round to a desired dumping point, the back door of the bucket is tripped open mechanically, and the operation commences all over again. It will be understood, therefore, that power shovel action is essentially outward, upward and positive due to rigid digging members mechanically controlled. In short, a magnification mechanically of the exact movements performed by a man digging with a hand shovel.

The Dragline.—The dragline may be simply called a rope-controlled scoop. Whereas the shovel only requires one power-driven hauling drum, the dragline requires two, one for the hoist and one for the horizontal dragging effort. In the dragline the mouth of the rope-controlled bucket faces the machine when the cut is commenced, and the dragline pulls
the bucket through the ground to be excavated, towards itself, so filling the bucket. The hoist then hoists the bucket clear, it swings to the dumping point, and the drag rope is let go causing the bucket to up-end and discharge. The dragline, therefore, may be considered a non-positive excavator, having a flexible rope controlled bucket instead of a rigid member control as in the case of the shovel. It cuts material upward towards itself.

Grabbing Excavator.—Two hauling drums and two power-operated wire ropes are again required. In this machine the bucket action may be simply likened to the human hand reaching down into the material and grabbing a handful. One rope is the lowering and bucket-opening rope, and the other is the hoisting and closing rope, each performing a dual function. Single rope grabs also can be obtained in which the mechanical control usually handled by the excavator machinery is built into the bucket.

A point which should be here stressed as a matter of interest is the fact that, broadly speaking, the standard excavator is rapidly convertible to any of the above uses. Admittedly different jibs and extra hauling drums are used, but as anchorages for these are provided on all first class machines before they leave the factory, it is only a two or three hours' job to fit the alternative equipment.

MACHINERY ARRANGEMENT ON EXCAVATORS.

The Standard Three-engined Steamer.—This arrangement consists of a suitable boiler supplying steam at proper pressure to three separate engines, one driving the hoisting drum, one the rotating mechanism, and a third, mounted on the jib, driving the digger handle thrusting mechanism. The hoisting drum is free on the shaft when disengaged, and is put into action by a steam ram applying a friction band engagement. Three operating levers, one for each motion, control these actions either forward or reverse, and the ram throttle is automatically actuated when passing in or out of the central neutral position in either direction.

With regard to steaming, it should be mentioned that boiler requirements for excavator work are somewhat different to most other forms of propulsion. Coal economy beyond a certain reasonable point is of rather secondary consideration. Ample and quick steaming to meet sudden load shocks is of paramount importance, remembering that full power is required for a few seconds only about three times per minute with next to no demand in the intervals. The said reasonable economy point is obtained by automatic throttling and by well-designed valve gears to give economical cut-off also automatically.
The old single-engined steamer of the earlier days had none of the modern refinements, and drove all three motions through a constantly rotating and highly uneconomical mass of transmission mechanism.

The modern railroad type steam excavator has practically the same characteristics as the full revolving steamer, except that, while in this type only the jib on its rotating base revolves, the engine of the latter transmits its effort to the rotating jib-base by means of a wire rope drive through suitable sheaves.

Single Motor Electric or Internal Combustion Enginned Machines.—In this type the motor or engine takes the place of the old-fashioned single steam engine, and distributes its power to the three main motions through the aforesaid mass of uneconomical transmission. This transmission consists of gear, frictions and clutches which eat up a good deal of power, and consequently fuel, over and above that used to produce useful work in the form of tonnage excavated.

Really and truly the only consideration to recommend the single motor arrangement is cheap first cost. This rather false initial economy sacrifices ultimate economy, which ultimate economy takes the form of immunity from heavy wear and tear, and fuel economy by reason of absence of power absorbing mechanical transmission. In some countries where operating labour is of low grade some people believe that plain mechanical wear and tear is preferable to imagined electrical complications supposed to exist in multi-motored machines. This is an entirely erroneous and unjustified viewpoint, but one which is, curiously enough, difficult to dispel.

The Two-motor Electric Machine.—This is really a compromise between the uneconomical single motor machine and the economical and efficient three-motor machine. Its only advantage over the single motor machine is the elimination of at least some of the mechanical transmission, and gives a slight advantage in original first cost.

The Three-motor Machine.—This is the truly economical and efficient machine, inasmuch as (when using voltage controlled direct current, which will be discussed shortly) all the desirable power, torque and speed characteristics of the three-engined steam excavator are obtained. This arrangement permits of an absolute minimum of mechanical transmission which is so very undesirable, and therefore gives an immunity from breakdown and fuel loss which is obtainable in no less complete arrangement. Obviously, if the three-engined steam machine is universally recognised as the ultimate ideal
in steam operation, a three-motor electric giving precisely the same characteristics must be the ideal electrically powered machine.

**Electrical Operation.**

It would be distinctly unwise in an account of this sort not to treat pretty fully on the vitally important matter of A.C. and D.C. in regard to excavator operation.

For many years the scientific application of electrical energy to excavator work was not very carefully considered. The main objective was to dig dirt mechanically, and so long as the power unit was strong enough to dig reasonably, economically and without undue electrical maintenance, either kind of current was used somewhat unquestioningly delivered direct to the operating motors of the excavator. Nowadays, however, mechanical excavation has become something of an exact science and current economy, fast no-load speeds, high torque at low speeds and regenerative braking have become matters of necessity. Using moderate voltage A.C. direct from power line to operating motors through suitable contactor control had a long period of popularity; it meant a minimum number of rotating units with comparatively low first cost and a certain amount of imaginary simplicity. Experience, however, brought home the facts that constant speed motors could not ever give high torque at low speeds when cutting through material, nor could they give any higher light load speeds than their maximum torque speeds.

It was the Marion Company who first pioneered the curing of these disadvantages. It was obvious that one could take A.C. from the line, convert it into low voltage D.C. by the use of a motor generator set; further, that by introducing differential opposed characteristics into the generator one could deliver current to the operating motors which would enable them to deliver their maximum torque at minimum speed and minimum voltage when starting the cut, accelerating as the resistance to motion decreased coming through and out of the cut, and giving maximum swinging and bucket return speeds. This system, known as the drooping voltage control, was standardised on the smaller electrical machines and has done marvellous service, has resulted in great economy (because of the low voltage and consequently low current consumption on heavy loads), and has, by its ever-increasing popularity, caused other first class makers to fall into line. Admittedly the system introduced two more rotating electric units on each excavator in the form of the motor generator set, but as this set is automatic in action and practically undamageable, this addition, when compared with the enormous advantages accruing therefrom, was trifling.
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A still further refinement along the same lines has been most successful standard practice on large electric excavators for some years. This is the Ward-Leonard Control.

It will be seen from the foregoing account of the drooping voltage control that the ideal electrical control for excavator practice is to control the torque speed and cutting characteristics by variable voltage and variable speeds. The supply of this variable voltage from one generator to three separate motors of widely different powers and duties is really only partially ideal, in so far as the one generator must be continually adjusting itself to different loads, and the small intervals between each adjustment mean slight losses.

The true ideal is to have a separate and suitable generator supplying variable voltage current for its own particular corresponding motor so as to lose no current whatever, and this, in simple language, is what Ward-Leonard Control really is. A motor taking line current is mounted with three low voltage D.C. differentially wound generators on a common base plate situated at the back of the excavator platform. One of these generators supplies the hoisting current, one the rotating and one the crowding or thrusting current. By this system variable voltage control is supplied to each motor by a separate generator of exactly suitable power range. By this means every unit of current produces its share of mechanical work at the bucket with an absolute minimum of mechanical loss, and accordingly the highest possible efficiency and economy is obtained. Furthermore, the loaded bucket, lowering from maximum height, drives the hoisting motor as a generator and pays current back into the system. This is a further economy.

THE GENERAL STATUS OF ELECTRICAL OPERATION.

Whilst contactor-controlled A.C. and D.C. current fed directly into the operating motors was standard practice for many years on the sole grounds of simplicity and first cost economy, it was found, compared with voltage-controlled current, from separate M.G. set, to be woefully inefficient and uneconomical, simply because the inevitable electrical and mechanical losses inherent in constant speed motors ate up an appreciable amount of current which was obviously not used in the production of useful mechanical effort at the digging point.

Partially technical and laymen alike often ask why it should be necessary, if the line power current be moderate voltage D.C. to begin with, to regenerate similar current for the motor supply, just the same as in the case of alternating
primary current. The answer is, of course, that the special M.G. set is necessary any way in order to introduce into the secondary generator the differential windings necessary to afford variable voltage feed. Obviously no straightforward line supply can give this.

Variable voltage control in electrical excavators has increased the speed of bucket operation by 20 per cent. to 25 per cent., in addition to materially reducing the consumption of current required for any given mechanical effort at the bucket. Small wonder is it, therefore, that all the first class firms building large electric excavators have fallen into line, and now, without exception, feature the Ward-Leonard Control.

**LARGE REVOLVING STEAM AND ELECTRIC SHOVELS AND DRAGLINES.**

Large revolving shovels are used mainly for stripping overburden off coal and minerals to a maximum depth of about 75 feet. Occasionally they are efficiently used to load deposits of minerals where depth of cut and fineness of product warrants. Large revolving draglines are used for cutting large canal works and for stripping loose overburden, maximum dragline reach being about 160 feet radially from machine centre.

Railroad Type Shovels.—Used almost exclusively for heavy quarrying and mineral mining owing to extreme sturdiness and ability to stand punishment. They are extremely limited as to boom reach, but great tonnage producers. They are not convertible into draglines.

Medium-size Full Revolving Shovels and Draglines.—These fulfil the same functions as the large types, but on more limited ranges of reach. The shovels combine the caterpillar mobility of the small machines with much of the sturdiness of the railroad type, and these machines, by reason of this, and the fact that they are full revolving, are doing much of the heavy quarry work which was hitherto the prerogative of the railroad type.

Small Revolving Shovels and Dragines, $\frac{3}{4}$ to $2\frac{1}{2}$ cu. yds.—These machines are at once the Jacks of all Trades as well as being the bread and butter class of the excavator business. They are used for every class of excavation known for which their reach and bucket capacity are sufficient. They are sturdy enough for heavy rock and mineral work. They are fast enough for shallow contract work. They are very mobile on caterpillars, and are readily convertible to a multiplicity of uses. They have very low unit pressure for work in soft ground, and are very fast.
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CYCLIC SPEEDS OF OPERATION.

As a matter of interest it might be mentioned that the 3-motor electric yard modern excavator can in reasonably easy going, such as say gravel, perform as much as four full cycles of operation per minute, whilst the big yard electric Ward-Leonard controlled shovel, having a 90 ft. jib and a 60 ft. dipper handle, has been repeatedly timed to perform a complete cycle in 40 seconds. With these latter machines a daily production of 4000 to 5000 tons is not by any means unusual.

EXCAVATOR POWER UNITS GOVERNED BY LOCAL FUEL SITUATION.

Where coal or fuel oil and reasonable boiler feed water are available at low or normal prices, and without undue haulage, and where duty is reasonably constant throughout the day, the steam excavator is probably advisable, because it is the simplest to maintain. The cost of excavation by steam power is practically the same as by electric power at very low rates.

The electrically-powered excavator, however, is decidedly indicated where fuel and water conditions are not of the best, and where current is available at low rates. The electric excavator is somewhat faster than the equivalent-sized steam machine by reason of its superior and more positive control. Trailing feeder cable is, of course, required, and where possibilities exist of the machine being required to exercise a large radius of action, current distribution expenses enter into the calculation as to respective desirability between steam and current.

Where coal, fuel oil and water are difficult or impossible to obtain, and where current is not available, the internal combustion engined excavator, or, better still, the internal combustion-electric machine, is obviously indicated. A great deal of the dragline field in arid countries presents just such conditions as these, and in these places the internal combustion power units have given good service, and are in great demand.

The choice between oil or coal fuel for steam machines is indicated by local conditions and availability.

THE DIESEL ENGINE APPLICATION TO EXCAVATOR PRACTICE.

Of recent years the oil engine as a power unit for excavators has been steadily advancing in popularity in many regions where steam and electric power are not readily available.
Several builders feature single-engined oil-engined excavators employing mechanical transmission, and, whilst field results have been quite reasonably good, the single-engined machine has suffered from all its old-time undesirability by having to overcome heavy mechanical losses in transmission. Not only this; whilst most makers producing this class of machine habitually use the word "Diesel," it is a fact that most engines yet used are really cold starting, crude oil engines, and not strictly Diesels. They have been, without exception up to date, all of the three or four cylinder comparatively slow speed type. As the oil engine is, of a necessity, always mounted at the rear of the working deck, and as its position is, therefore, always on the extremity of the overhung structure, the high vibration of the engine has been experienced throughout the machine. The machines have, furthermore, been rendered extremely disagreeable to operators by reason of high continuous vibration. Fortunately there are at present being perfected several makes of crude oil engines having much higher normal speeds. These will eliminate a good deal of the vibration. These engines are also, by reason of their high speed, considerably lighter than the present ones, and will, therefore, cut down some of the high first cost which has mitigated somewhat against the so-called Diesel-engined excavator.

THE DIESEL-ELECTRIC EXCAVATOR.

Newer, lighter, and higher speed oil engines will facilitate the development of the Diesel-electric excavator, a machine which has all the virtues of the three-motor full electric, but which has, of course, an oil engine instead of an electric motor in the generator set. This combination represents the highest grade and most economical practice possible, although somewhat higher in first cost than the friction type machine.

It is practically certain the development of the Diesel-electric excavator will gradually spread to the larger sizes. Where the size of the machine involves a heavier engine than ought to go on the after deck of the excavator, there seems no doubt that the actual excavator will be a simple full electric, towing behind itself by rigid tow-rods its own Diesel-electric mobile power plant. The high fuel economy of the Diesel engine is just as desirable to this class of machinery as to any other, especially in comparatively waterless countries.

EXCAVATORS IN VARIOUS COUNTRIES.

It is not out of place to ask ourselves the question: "Just where are excavators required?"
It has been admitted that only in the United States, and possibly Canada, does one see the power excavator fully realising all its possibilities. There they are put to every conceivable use for which they can be employed, firstly because comparatively no manual rough labour is available, and secondly because mechanical excavation is much cheaper in any case. The coal, iron and copper of the United States are mined by excavators. Roads and railways use them for excavation, basements are dug by them, irrigation and reclamation works, large and small, are all draglined; in fact, every job of digging and material handling is done mechanically. Many thousands of power excavators are in daily use in the United States, and one is often tempted to feel that surely one must soon reach a saturation point where only replacement machines can be sold. But no, builders of excavating machinery are building and selling more machines to-day than ever, and it is quite safe to say that in the United States sales of excavators exceed twenty per day.

As justification for this extraordinary state of affairs it must be remembered that the United States—a country larger than all Europe—has been developed industrially and socially to a pitch at least equal to the better European countries in a period not exceeding fifty years. Naturally this took some altering of the landscape, hence the enormous amount of mechanical excavation. Despite much progress in recent years, Europe, Australia, Asia and Africa are only taking their first toddling steps in the enormous possibilities of mechanical excavation, and the prospects of these countries are potentially wonderful.

It is not out of place at this point to say just a few words more about the business of extremely heavy duty for the excavators in open strip mineral mining, limestone and road metal quarrying. The general purpose excavator of yesterday was, perhaps, all very well for its general duties, but in these days of high speed and heavy duty production of metal and stone the somewhat lightly-built excavator has ceased to have its day, and the trend of design of the most extensive excavator builders to-day is towards exceptionally powerful machinery, very largely constructed of heat-treated alloy cast steels.

The excavator of to-day, working in the high-speed production of metal and stone, has to stand up to a weight of punishment hitherto unknown, and no mere excavator of non-specialised construction can stand this punishment, and while a great many users still believe that the old-fashioned structural steel construction is good enough, there is no getting beyond the fact that it is not good enough for heavy produc-
tion at high speed, and it is only heavy production at high speed which can get production costs down to a level where adequate profit can result to the user in these days of keen competition.

The President thought the paper was of extreme value, and given in such a subtle manner that it was almost above criticism. The subject was a special study that the ordinary engineer could hardly discuss in detail. He would content himself with moving a hearty vote of thanks to Mr. Fairhurst for his interesting lecture.

Mr. A. E. Hughes, supporting the President, said he had listened to the lecture with very great interest. The paper was replete with interesting points, many of which to him were quite new. The adaptation of an electric motor generator set to generate electricity at three different voltages, or different characteristics, was new to him. There were adaptations of that particular phase that probably could be utilised in factory work. But the paper was such an extensive one that it would be necessary to study it before an intelligent discussion could take place.

Mr. V. Dam endorsed the remarks of Mr. Hughes. Many of the features referred to in the lecture were entirely new to him. The lecture had been most informative, and had traced the evolution of excavators. It would enable one to make an intelligent selection of what might be the best type to adopt.

Mr. Malcolm Moore said people interested in excavating machinery must appreciate the fact that a representative of one of the companies was prepared to give them the information that had cost many years of work and financial outlay to collate. Where he had seen the Ward-Leonard control in other types of machines it had been a direct drive to the main drum, without an air clutch. He would like to ask why it was necessary to have the air clutch in conjunction with the control?

Mr. Bailey added his thanks to the lecturer for a very interesting paper, to which he had listened with very great interest. He had appreciated many of the points in the lecture, and hoped to hear more from Mr. Fairhurst at a later date.

Mr. A. Lewis said he had appreciated the paper very much. With reference to the somewhat disparaging remarks as to the single-motor machine, he had seen one of a very inferior appearance in operation in 1910, and it was still in commission. He considered the paper a very valuable addition to the Proceedings.
Mr. BARWICK asked—(1) As to the shovel, what was the reason for putting the crowding arm through the middle of the bar? (2) As to dragline excavators, what was the reason for the very elaborate guiding of the rope immediately in front of the machine?

Mr. T. W. FAIRHURST, in reply, referred to the point raised as to the use of the air clutch with the Ward-Leonard control. There was no doubt the apparatus could be used without the air clutch, but it was of great assistance. The main point was that it was necessary to have some initial motion before the load was applied, and the air clutch would give one-seventh of the motion before applying the load. They could do without it, but would not obtain as smooth action; and when it was considered that the machine was moving some tons of earth, it would be realised they were looking for smoothness all the time.

There were numbers of engines of the half-yard type built with single-engine control. Very often those machines stood up for many years. But if they were employed on work in which underlying rock was encountered, it would be found they could not last six months.

Then he had been asked as to why the dipper stick ran through the boom rather than round it? It was a moot point. There was something to be said both ways. What his firm aimed at was resilience—ability to stand punishment and resume the normal condition. With the steel boom straddled by dipper stick a good deal of contortion occurred. The theory of the two arms holding the bucket was that it was supposed to secure better control of the bucket, and those who advocated the double arm referred to the absurdity of trying to plough with a one-handled plough. However, the reply was that in this case they were not ploughing, but digging, and they had not yet seen a man digging with a two-handled spade. In the event of the bucket being twisted out of position by striking a corner on a rock, the single-handled device would return to its position with much more resilience than would the double.

As to the elaborateness of what were known as the fair leads in the dragline, it was somewhat difficult to answer. The dragline rope operated at very high speed, and was frequently covered with mud. Furthermore, it worked on a curved drum. If there were no fair-lead to guide the rope, the first happening would be a climbing drum. The wear upon the rope was quite sufficient without that. The depreciation of those ropes was one of the most expensive items in the plant. Therefore they used the fair-lead to give the rope a true angle of entry on to the drum.