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Erosion of the slopes of gold-residue dams on the Transvaal Highveld—preliminary results

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SYNOPSIS

The paper describes a study of rates of erosion from the slopes of gold-residue dams. As the available data are for only two years, the conclusions must be regarded as tentative. Nevertheless, some useful correlations were established that enable quantitative predictions to be made of the annual tonnage of residue that will be lost from a slope. Designers could use this information when designing the capacity of erosion-containing structures such as toe-paddock dams, estimating desilting requirements, and deciding whether a slope will require protection against erosion.

SAMEVATTING

Die referaat beskryf 'n studie van die erosietempo van die hellings van goudresidudamme. Aangesien die beskikbare data net twee jaar dek, moet die gevolgtrekkings as tentatief beskou word. Daar is nietemin 'n paar nuttige korrelasies vasgestel wat dit moontlik maak om kwantitatiewe voorspellings te maak oor die jaarlikse tonnemaat residu wat van 'n helling verlore sal gaan. Ontwerpers kan hierdie inligting gebruik by die ontwerp van die inhoudsvermoë van strukture om erosie te keer soos voetkampdamme, die beraming van ontslikvereistes, en die besluit of 'n helling teen erosie beskerm moet word.

Introduction

Gold residue is a highly erodible, silty material which, when it escapes from the confines of a dam, can cause extensive siltation of streams, rivers, low-lying areas, and agricultural land. Dust pollution emanating from gold-residue dams may also reach unacceptable levels.

Considerable time, effort, and expense have gone into devising and implementing measures to prevent, or at least abate, the polluting effects of gold-residue dams[1-3]. The *Chamber of Mines Guidelines for Environmental Protection*[1] require the provision of toe paddocks or bund walls round every dam to contain material eroded from the slopes. Because there is no information on the rates of erosion from the slopes of residue dams, and no theoretical or empirical basis for the estimation of rates of erosion, the silt-retaining capacity required of these paddock dams can only be guessed at. Once a residue dam is due for closure, a decision must be made as to whether or not the slopes require protection from erosion. The *Chamber of Mines Guidelines* advocate the use of the ETCOM erosion tester to establish an index of the erodibility of a slope surface. To quote from the *Guidelines*: 'The tester is used to direct a jet of water vertically downwards towards the slope from an orifice 0,8 mm in diameter, which is located 25 mm away from the surface . . . . The pressure of the jet is increased at a constant rate from substantially zero until dislodgement of surface material occurs. The jet pressure in kilopascals at which dislodgement is first observed is known as the ETCOM erosion index for the surface.' The *Guidelines* then set out recommended remedial action for various ranges of the erosion index, the indication being that the erodibility of a surface decreases as the erosion index increases. However, no correlation between erosion index and rate of erosion has so far been published.

The purpose of the work described in this paper was to investigate actual rates of erosion from residue dams in the Transvaal Highveld region. The method used is one suggested in the *Guidelines*: 'To establish a base from which the progress of future erosion may be monitored, a corrosion resisting rod should be driven normally to the side slope of the deposit and down to a mark thereon at each test point. The progress of erosion with time as measured from the initial mark on the rod, should be correlated with the initial test information as determined above'. (The initial test information is the erosion index.)

Mechanics of Soil Erosion

Extensive research into the mechanics of soil erosion has been carried out in the fields of agricultural science, river mechanics, and related areas. The subject is so complex that, although fundamental mechanisms are understood, it has not proved possible to formulate a general theory or a completely rational set of equations describing the erosion process. The most successful ways of predicting quantities of soil loss through erosion remain semi-empirical.

Because agricultural fields, river beds, etc. invariably have flat slopes, it is generally not possible to extrapolate the results of studies on agricultural or riverine erosion to the very steep slopes of mining-residue dams. For example, a slope of 15 degrees would be excessively steep in agricultural practice, but impracticably flat for the sides of a residue dam.

What follows is not intended to be an exhaustive review of the theory of erosion, but to serve as an introduction to the factors that appear most important in slope ero-

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sion by rain and surface run-off and, in dry weather, by wind.

Erosion by water can be defined by two sub-processes: detachment by rainfall and detachment by runoff.

Raindrops hitting the surface dislodge particles, which are then carried downslope in increasing quantities as the flowrate increases. A single drop falling on a slope in still air conditions has components of momentum normal to, and down, the slope. The downslope component of the weight of the drop is transferred in full to the surface but only a small proportion of the component normal to the surface is transferred, the remainder being reflected. The transference of momentum to the particles has two effects: it provides a consolidating force, compacting the surface; and it imparts a velocity to some of the loosened particles and launches them into the air. This process is continued down the slope by transfer of momentum, and the jumping or saltating* process is repeated.

When rain is accompanied by wind, there is an added wind-velocity component of momentum, and the resultant force as the drop strikes may be greater than for a drop falling in still air. Hǒlý[4] states that rainsplash is more effective in dislodging particles as the angle of the slope steepens, especially with wind.

Studies have shown that, as the depth of the surface water increases, so does the erosion by rainsplash. This is believed to be due to the turbulence that impacting raindrops impart to the water. However, there is a critical depth beyond which the erosion decreases again because all the energy is dissipated in the water and does not disturb the soil surface. Hǒlý states that this critical depth is approximately equal to the diameter of the raindrops. Hudson[5] established that the maximum diameter of rain drops is 5 mm, and this is usually reached in the highly intense rainfall that is peculiar to the Transvaal.

The bulk of the water erosion from residue dams probably arises from detachment by runoff. Runoff occurs during a rainstorm when the moisture storage or infiltration capacity has been exceeded. For the flow of water to detach the particles, a certain tractive force related to the flow velocity has to be reached.

Bagnold[6] related the tractive force to flow velocity and particle size. He found that the critical flow velocity required for particles to become detached decreases with decreasing grain size, but below a certain particle size (about 0,1 mm, which is larger than most gold-residue particles) the critical velocity increases again.

Hjulstrom[7] determined a relationship between particle size and critical velocity for erosion. His data support those of Bagnold, and show, for instance, that the critical velocity for a particle size of 0,1 mm is about 0,2 m/s, for 1 mm it is 0,3 m/s, and for 0,01 mm it rises to 0,8 m/s.

The process of erosion by wind is basically similar to that by water. In order to be eroded, a particle must be detached by tractive forces. To be transported, it must acquire kinetic energy from the wind. Once this has occurred, solid particles above a certain size will saltate* and finer particles may be carried in suspension.

Bagnold[8] shows that the rate of saltation in wind is directly proportional to the square root of the particle size, and to the cube of the difference between the wind speed and the threshold wind speed for particle pick-up. The threshold wind speed is directly proportional to the particle size or diameter. However, this applies only to particles larger in size than about 0,1 mm. Finer material becomes airborne when kinetic energy is imparted to it by saltating larger grains. The rate at which dust goes into suspension thus becomes roughly proportional to the rate at which larger particles are saltating (Gillette *et al.*[9]).

Some attempts have been made to evaluate erodibility by means of submerged jets directed at soil surfaces. Dunn[10] attempted to relate erodibility as measured by a submerged jet to the shear strength of the soil composing the eroding surface. The attempt was only partly successful, apparently because of the highly irregular and fluctuating force field applied to the surface by an impinging jet.

By far the most widely used method for the prediction of soil erosion appears to be the Universal Soil Loss Equation (USLE), which was developed by soil conservationists in the U.S.A. and modified for regional use (e.g. Evans and Kalkaris[11]). The equation is semi-empirical in that it incorporates terms to account for the factors known to be most important in the erosion process, but uses empirical values for them. The equation is

$$E = ARKLSCP,$$

in which

E is the soil loss in mass per area units
A is a constant that is usually taken as 2,24
R is a rainfall factor related to the kinetic energy of falling rain
K is an erodibility index
LS is a topographic factor accounting for the combined effect of slope length L and slope angle S
C is a cropping-management factor
P is an erosion control factor.

Of these factors, R is the most important, since AR represents the soil loss whereas K, LS, C, and P are all modifying factors.

For the present investigation, the slope parameters that can be controlled or measured by the engineer were selected, and correlations were established between them and measured rates of erosion. It was clear that insufficient data and experience would be available to formulate an equivalent USLE for gold-residue dams at present. This might become a longer-term objective.

The following parameters and dimensions were selected for correlation: ETCOM erosion index, shear strength of the slope surface, slope length, and slope angle.

Experimental Work

Ten experimental plots were set up on seven gold-residue dams on the Witwatersrand. The plots each measured 9 by 9 m, and were chosen to have differing aspects, slope lengths, and slope angles. Steel pegs of 8 mm diameter and 1 m in length were driven normal to the slope at 3 m intervals, giving a 4-by-4 peg array of 16 pegs in total. A section of each peg, 250 mm accurately measured, was left proud of the ground. As the posi-

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* A saltating particle progresses along the surface in a series of leaps and bounds, being alternately picked up by the wind and deposited on the surface.

tioning of the plot is important if the measurements are to be representative, the plots were positioned approximately in the middle of the slope length. It was assumed that the least erosion would occur at the top of the slope, and the most at the bottom*. An average value should therefore be obtained at the centre of the slope. Pegs were driven on an exact grid. As a result, some were located in erosion rills, some on the ridges between rills, and some in intermediate positions.

Rain gauges were initially set up on five of the seven residue dams, but, as a result of persistent vandalism, there are no complete rainfall records for the test period. Because the dams are located reasonably close to the Rand and Jan Smuts airports, the rainfall at these two places was taken to represent the rainfall at the experimental plots.

From the average measured surface retreat on the experimental plots and the measured dry density of the residue at each plot, the annual rate of erosion in tons per hectare was calculated for both summer and winter. (Summer was defined for this purpose as the months of October to March, while winter was taken as the months of April to September.)

In addition to the measurement of the retreat, measurements were made of the ETCOM erosion index and of the shear strength of the residue surfaces.

Shear strengths were measured by means of a handheld miniature vane, which penetrates the surface to a depth of 5 mm and thus measures the shear strength of the surface skin that is directly affected by erosion. To eliminate capillary stresses that would have unrealistically increased the shear strength, water was poured over the test area and was then allowed to seep away before the vane was used.

At the time of writing, the results for only two calendar years are available. These span from April 1984 to March 1986. The total rainfall for the test period recorded at Rand Airport was 598 mm for the first year and 761 mm for the second. The long-term average for this station is not known since records have been kept there only for the past four years. However, the annual rainfall for Jan Smuts airport over the test period was only 7 per cent less than the 30-year average (644 mm and 711 mm, as against 726 mm). Hence, unless there are particularly wide local variations, the rainfall for the test period does not appear to have been abnormal.

The first surprise given by the measured erosion rates was that erosion in the first winter averaged only slightly less than that in the first summer. Although the winter rainfall was only 10,3 per cent of the summer rainfall, winter erosion exceeded summer erosion in some cases. For the ten test plots, the average summer erosion was 145 t/ha, whereas the average winter erosion was 120 t/ha, i.e. the winter erosion averaged 83 per cent of the summer erosion. For individual plots, the winter erosion varied between 45 and 138 per cent of the summer erosion. Hence, there appears to be a large component of wind erosion in the total erosion figure. It is likely that wind action also causes a significant proportion of the summer erosion.

Once of the above findings became known, the rainfall figures assumed less significance, and it was decided not to differentiate between winter and summer erosion at this stage, or to consider erosion per unit rainfall, but to attempt most correlations on the basis of total annual erosion.

Table I summarizes the available data for the ten test slopes.

Correlations Between Erosion Loss and Various Parameters

Erosion Versus ETCOM Erosion Index

Fig. 1 shows two correlations: between the average ETCOM erosion index measured in summer and in winter, and the residue loss by erosion (in this case, expressed as erosion loss per season, either summer or winter).

Rather surprisingly, the correlations, although not strong, are positive, i.e. erosion loss increases with increasing ETCOM reading. The explanation for this is not entirely clear. However, ETCOM measurements are made on a desiccated surface, where much of the strength and penetration resistance probably arise from capillary stresses. Hence, finer material, in which the capillary stresses can be larger, can be expected to give higher

TABLE I
SUMMARIZED DATA FROM EROSION MEASUREMENTS

Slope	Erosion loss, E				Average ETCOM kPa	Surface shear strength, τ kPa		Slope length, L m	Slope angle, S	
	Winter 1 t/ha	Summer 1 t/ha	Total annual							
			Year 1	2-year mean		Year 1	Year 2		Arc °	%
3L39E	108	140	248	214	138	335	400	34	33	66
4L34S	154	342	496	353	102	290	270	25	37	75
Balmoral N	110	206	316	277	152	315	290	23	32	63
4L37N	74	91	165	197	126	305	460	22	35	70
4L37E	217	176	393	298	114	315	370	42	36	72
4L36N	186	172	358	294	209	345	170	49	33	64
4L36E	87	109	196	187	125	245	210	26	31	60
4L24S	77	70	147	158	85	350	400	25	46	105
4L40S	116	84	200	204	72	355	360	25	25	46
4L40W	72	61	133	236	70	355	420	30	37	75

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* Measurements on individual pegs have confirmed this assumption. The pegs in the top row of each plot show considerably lower erosion rates than those in the bottom row.

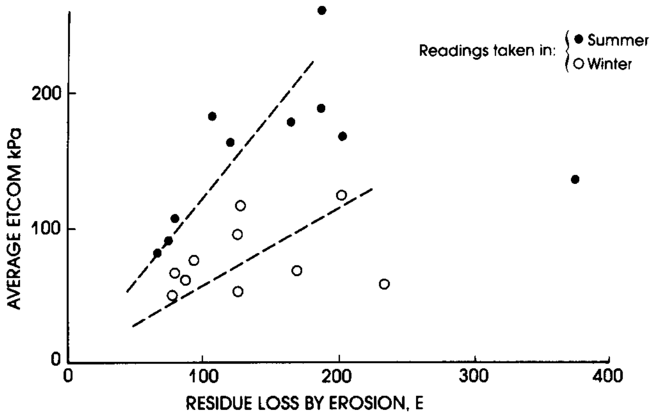


Fig. 1—Correlation between ETCOM erosion index and seasonal residue loss by erosion in tons per hectare

ETCOM readings. The postulated role of capillary stresses is supported by the fact that the summer readings shown in Fig. 1 are generally greater than the winter readings. The higher temperatures in summer can be expected to result in higher capillary stresses, and hence higher ETCOM values. When rain wets the surface, the capillary stresses disappear and finer materials then become more erodible than coarser.

Fig. 2 shows the annual residue loss plotted against the mean of the average summer and winter ETCOM readings. Although there are considerable scatter and some outlying points, the correlation line could be used as a basis for the prediction of erosion losses.

Erosion Versus Shear Strength

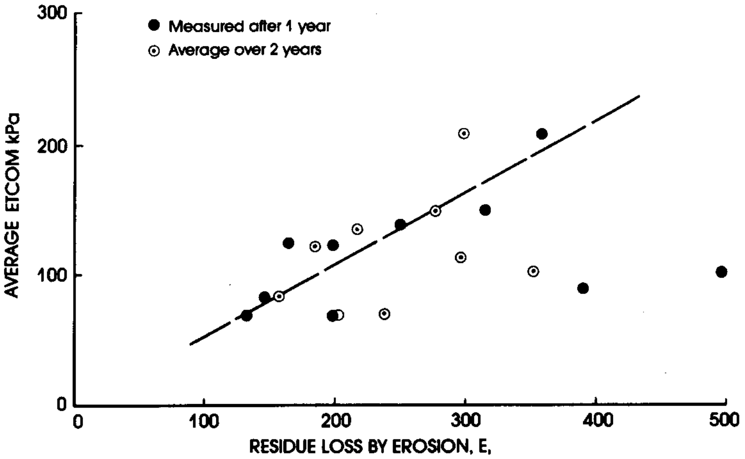
The correlation between erosion loss and surface shear strength, measured by hand vane on a saturated surface, is shown in Fig. 3.

The measurements made over the first year gave a poor correlation, with a wide range of erosion losses corresponding to a particular shear strength. The measurements representing the average over two years gave a somewhat better correlation, although still with a great deal of scatter. The correlation is reasonable in that the annual erosion loss would be expected to increase as the shear strength of the slope surface, and hence the tractive force required for particle detachment, decreased.

Erosion Versus Slope Length

Fig. 4 shows the relationship between erosion loss and slope length. Here, again, the correlation is reasonably good for slopes longer than 25 m. The data for slopes less than 25 m in length show considerable scatter, probably because of the influence of varying slope angle, surface

Fig. 2—Correlation between average summer and winter ETCOM erosion index and annual residue loss by erosion in tons per hectare



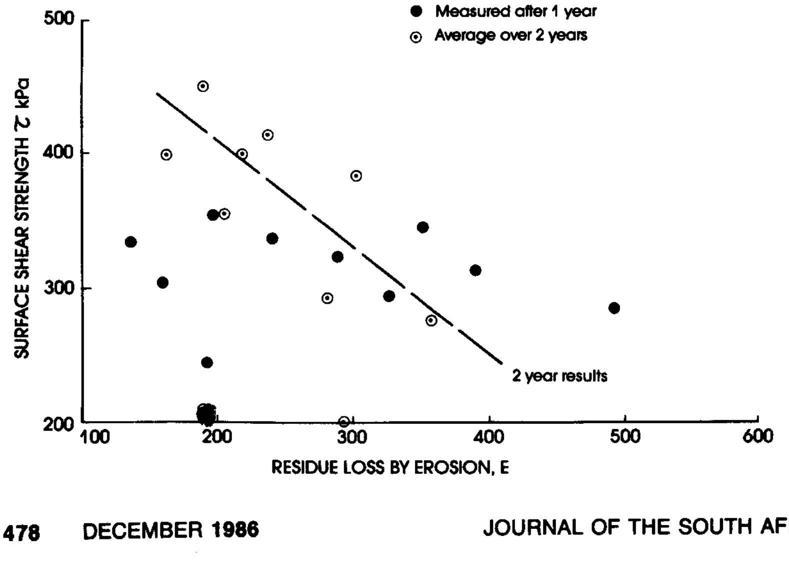


Fig. 3—Correlation between surface shear strength and annual residue loss by erosion in tons per hectare

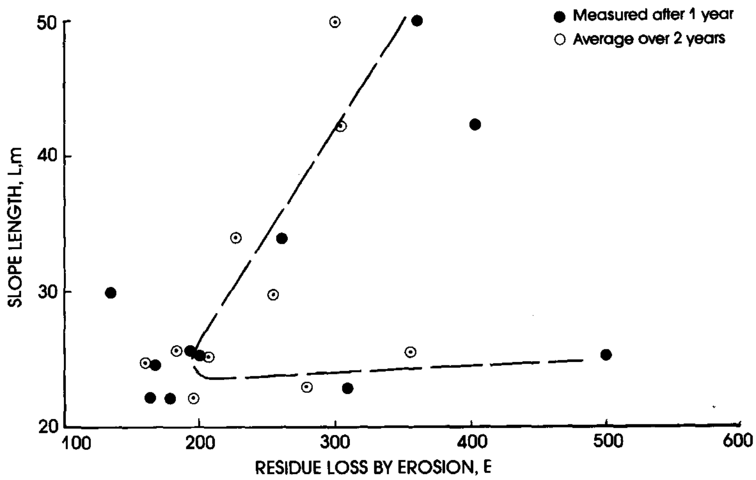


Fig. 4—Correlation between slope length and annual residue loss by erosion in tons per hectare

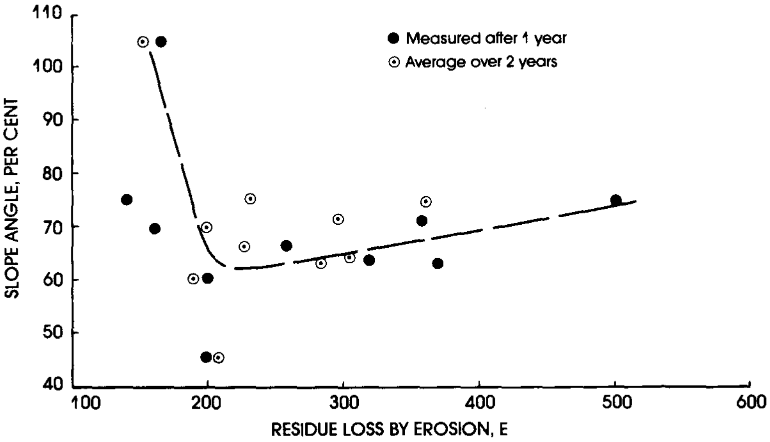


Fig. 5—Correlation between slope angle and annual residue loss by erosion in tons per hectare

shear strength, etc. For slopes longer than 25 m, the diagram gives some guidance on the influence of slope length on residue loss by erosion.

Erosion Versus Slope Angle

The correlation between slope angle and erosion loss is shown in Fig. 5. In this diagram, the slope angle is expressed as a percentage gradient, e.g. an angle of 45 degrees corresponds to 100 per cent and an angle of 30 degrees to 58 per cent. The reason for expressing the slope angle in this way, is that S in the USLE is expressed as a percentage.

As Fig. 5 shows, the correlation has a double value. For a slope angle of 70 per cent, for example, the average annual erosion loss could either be about 200 t/ha or 400 t/ha. It appears from the curve that, as the slope steepens, the erosion loss approaches a constant value of about 150 t/ha. The reason for the double-valued correlation of erosion rate with slope length is by no means obvious.

Slope aspect does not appear to be a factor. Of the erosion rates for slopes between 65 and 75 per cent in Fig. 5, two slopes faced north, two east, and one each faced south and west. Annual erosion rates of less than 200 t/ha were recorded on a north- and west-facing slope, while annual rates greater than 300 t/ha were recorded on north-, east-, and south-facing slopes. Different slope lengths do not seem to explain the phenomenon. The four data points in Fig. 5 for a slope of 75 per cent have slope lengths of 30 m (annual erosion loss in the region of 200 t/ha) and 25 m (annual erosion loss in the region of 400 t/ha).

The most likely explanation appears to lie in differences of shear strength. For the two slopes just considered, that with a high erosion loss had a mean shear strength of 280 kPa, while the slightly longer slope of the same angle that eroded only half as much had a mean shear strength of 380 kPa.

Use of Correlations to Predict Erosion Rates

Because of the uncertainty in the correlations established so far, it is recommended that the annual erosion rates shown in Figs. 2 to 5 should be used in conjunction in the prediction of erosion rates. If an example is taken at random from Table I, say 4L36N,

ETCOM $= 209$ kPa $\therefore E = 380$ t/ha from Fig. 2
Mean $\tau = 260$ kPa $\therefore E = 390$ t/ha from Fig. 3
$L = 49$ m $\therefore E = 350$ t/ha from Fig. 4
$S = 64\%$ $\therefore E = 290$ t/ha from Fig. 5 (ignoring lower value on graph)

Mean annual estimated $E = 350$ t/ha
Observed annual 2-year average $E = 294$ t/ha.

As indicated earlier, the value of annual erosion rate given above includes components of wind and water erosion. The present state of knowledge does not allow accurate apportionment of the total between the two components. As an interim measure, it is suggested that two-thirds of the total erosion rate should be assigned to water erosion and one-third to wind erosion.

As a design value, two-thirds of either the mean estimated or the largest estimated *E* could be adopted for the capacity of erosion-containing structures such as toe-paddock dams. The data could also be used as a basis in estimating de-silting requirements, and hence maintenance costs, for erosion-containing structures, and in deciding whether a given dam or slope needs to be protected by some means against erosion.

Conclusion

The research described in this paper identified the more important factors affecting erosion from the slopes of gold-residue dams. It demonstrated that wind erosion must be a very significant component of the total annual erosion from a slope. It has, for the first time, provided quantitative information on rates of erosion from residue dams. This information is, as yet, tentative and may apply only to conditions on the Transvaal Highveld.

Suggestions for Future Research

As stated earlier, this paper is based on the data obtained over only two years. It is essential that these measurements should be continued at the various sites for at least another three years as confirmation or otherwise of these preliminary findings.

The measurement of rates of accretion in toe paddocks would also be useful. Not only should these measurements support those made on the slopes, but they would give a useful indication of the comparative contribution, both in summer and winter, by wind and water erosion.

Measurements of erosion rates from the top surfaces of dams would also be of interest, as would measurements on cement-stabilized surfaces.

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Is engineering a limited profession?

Business expertise, it would appear, is the name of the game in the struggle to reach the top and finally land that coveted seat on the board. People from all walks of life, including those who have laboured long and hard to become experts in the engineering profession, have now agreed that business acumen and financial know-how are essential when it comes to wheeler-dealing in the corridors of power.

The sky is now the limit for engineers aiming for the top. As graduates, they can be admitted to the University of Cape Town's Accountants' Conversion Course, which enables them to expand their horizons and add chartered accountancy to their qualifications. This is possible with as little as one year away from work. The normal route to becoming a chartered accountant is to spend three years on a B.Com. course, followed by three years of articles, including a year of part-time study. This total of six years is usually just too long for people who have already completed one degree and have begun working.

The UCT conversion course allows a graduate engineer to complete, in just one year of fulltime study, the missing courses necessary for the core of the B.Com. This is then followed by the three years of articles, including a year of part-time study. This option provides a valuable opportunity for anyone who is desperately looking for a chance to improve his prospects in the business world but who cannot afford to be without an income for more than a year. Most of the normal routes to a professional qualification are expensive in terms of time away from work, and therefore earning potential. But the conversion course at UCT obviates that to a large extent, being short enough to be feasible for any determined graduate.

There is no doubt that parallel qualifications of this nature are not only desirable but are becoming increasingly essential worldwide. For admission criteria and details contact

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