Effect Of Off-Take Angles On Spatial Distribution Of Silt Materials At Concave Channel Bifurcation

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Abstract

A meandering physical channel was constructed and used to investigate the effect of off-take angles on suspended sediment distribution at concave channel bifurcation. Four different off-take angles of 30^0, 45^0, 60^0 and 90^0 with varied main channel flow rates Q_{16}, Q_{17} , Q_{18}, and Q_{19} were used for the study. Predicting statistical equations dependent on the off-take angles and main channel discharges for the evaluation of the tributary channel sediment intake were developed. Results of the studies showed that even with constant main channel discharge, the tributary channel sediment intake increased significantly with higher off-take angles. It was observed that the predicting equation under estimated the tributary channel sediment yield for off-take angles between 30^o – 70^o and for those between 70^o - 90^o the sediment values were over estimated for all the main channel flow rates considered. The predicting tributary sediment values equaled the experimental values at the off-take angles of 50^o – 70^o but varied differently for each of the main channel flow rates. It could be seen from the various off-take angles considered that the divergence in results obtained from the experimental works and predicting equation is in the range of 2.9% - 17.8% for minimum main channel flow rate and 12% - 36% for maximum main channel flow rate suggesting that the predicting equation could be useful in the evaluation of sediment yield at concave channel bifurcation.

Keywords: concave section, off-take angles, channel bifurcation, flow rates and suspended sediment.

NOTATIONS

Q_{16}, Q_{17} , Q_{18}, Q_{19} Main channel discharges;
Q_3 Off-take discharge
q_1, q_3 Main and Off-take channel specific discharges
α_0, α_1, α_2, α_3 Regression constants;
θ Off-take angle
S_1 Measured main channel sediment concentration
$M(S_3)$ Measured off-take channel sediment concentration
$P(S_3)$ Predicted off-take channel sediment concentration
R Correlation Coefficient

Introduction

A bifurcation occurs when a river or stream splits into two branches and naturally, it occurs when a middle bar forms in a channel or a distributary carries flow from the main river.

In the case of a meandering river/stream, the outer curve alignment is known as the concave part of the channel. When an intake is sited on this part of the curve as is the case of the Obinna river intake works supplying water to Adani rice farm at Nsukka in Enugu State, Nigeria, it is said to have a concave channel bifurcation. According to Abdel (1949), the angle that the off-take channel makes with the outer part of the main channel is called the off-take angle, or angle of Twist/Diversion. Some of the factors that may influence suspended and bed load sediment distribution includes main channel discharge, geometry and streamlining of bifurcation and conditions of the approaching channel.

The study of flow diversion and development of equations that model the physical movement of suspended sediment through bifurcations and confluences in open channels are still in progress. It is the desire of most hydraulic engineers to minimize the amount of sediment being transported by the rivers/streams into the branching canal. The sediment delivery if not controlled may lead to some attendant problems such as frequent breakdown of the installations downstream like pumps and turbines, reduction in flow capacity and vegetation growth due to sedimentation, erosion of channel walls due to the transport of rough materials, dredging of accumulated sediment is quite expensive and may cause interruption in water supply (Neary et al, 1993). According to Shen and Julien, (1993); Krishnappan, (1990); and Ziegler and Nisbet, (1994) the understanding of sediment transport in rivers and streams is extensive. However, the pattern of movement of fine grained particles through multi-channel systems is still very unclear. Pickup and

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Higgins, (1979) investigated sediment transport in braided river by treated the system as a multi-channel network, though their work was limited to bed-load transport. Fassnacht (1997) has examined the suspended sediment transport through multi-channel systems using mass balance theory at bifurcations and confluences. In spite of the challenges imposed by the undefined nature of sediment transport pattern at channel bifurcations, water diverted for domestic purposes is expected to be sediment free while water for power generation has definite limits on sediment content. According to Mosonyi (1965), high head plants with over 100m should not contain sediments larger than 0.01mm while for medium head plants the sediment size should be smaller than 0.5mm to avoid severe and rapid erosion of the turbines. Habermaas (1935) conducted series of model experiments on sediment distribution at river bifurcations in various channel curvatures, though he arbitrary sited the off take channels without considering the influence of the off take angles and variation in main channel discharge. Vries (1992) stated that the sediment distribution ratio into branches could be determined by local three-dimensional flow pattern. Wang et al. (1993) emphasized that the determination of the sediment distribution ratio (S_1/S_2) is a difficult task which resulted in several nodal point relations as solution.

Similarly Tarekul Islam et al (1997), Dekker and Van Voorthuizen (1994), Roosjen and Zwauenberg (1995) and Hannan (1995) have studied the morphology of a symmetrical river bifurcation with the help of physical models which concentrated on the distribution of sediment over the downstream branches with nose angle as the major variable.

The determination of the optimum off-take angle to limit the rate of siltation of the secondary canals would obviously reduce the frequency of dredging and ultimately minimize the total cost associated with the operation and maintenance of installations downstream.

As engineers become involved in managing rivers for new environmental purposes, reliable prediction tools and models should be available to examine the performance of various design options.

Consultants and Hydraulic engineers particularly those responsible for the planning of water projects may be expected to consider the optimum off-take angle for the concave channel bifurcation as one of the important factors to be considered in the alignment of the off-take channels.

Materials and Method

Experimental Setup

When a hydraulic problem is beyond an analytical solution, physical and numerical models could be used to address such problems which may include sediment transport problems (Chanson, 1999). Physical models are commonly used to optimize structural designs or ensure that a structure can operate properly (Chanson, 1999).The physical model used for the experimental work was constructed using metal sheets on scale ratios of 1:50 for horizontal and 1:15 for the vertical with a distortion of 3.30 and covering about 200m of the river channel. Three structural metal sheets having a width of 30cm each were welded together to form the base and walls of the main channel which represents fixed banks and bed of a natural river/stream. The main rectangular channel was 850cm long with straight and meandering features. Similarly, the off-take channels having width of 10cm and length of 90cm each were welded together to form the base and walls of the branch channels. Four number rectangular branch channels were designed and constructed such that the fitting ends would have one of the required off-take angles (30^o, 45^o, 60^o and 90^o) after welding them to the main channel. The upstream and downstream sections of the main channel were covered with square metal sheets of 30cm by 30cm by welding to maintain the water level required while the experiment was in progress. The downstream section was provided with a spillway to drain excess water from the main channel. At the invert level of -15cm, a rectangular opening was created on the main channel at the concave side of the model and branching channels were introduced to form the bifurcation. The meandering section of the model has an outer and inner radius of 135cm and 105cm respectively indicating a mild bend that would not require future river training works. The detailed plan views of the model and its cross section are shown in Figure 1.

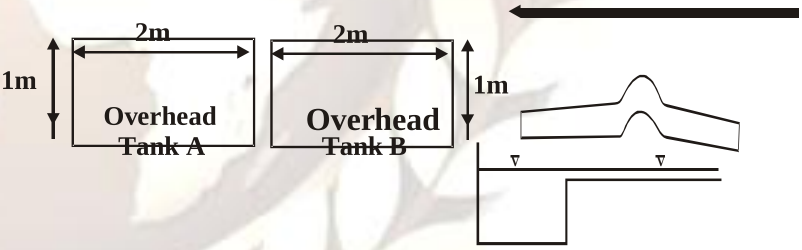

Fig. 1: Plan views of main channel, off-take channel and cross- section.

Experimental Procedure

The experimental work was carried out at the hydraulic laboratory of the Civil Engineering Department, University of Nigeria, Nsukka in Enugu State of Nigeria. The experiment set up was sub divided into three major components namely the water supply unit, the sediment supply unit and the regulatory/measuring unit. The circulation of water within the model was a closed system with a sediment trap provided at downstream section where water flows through a filter medium as it outfalls into the sump.

The measurement of the sediment distribution patterns at concave channel bifurcation was conducted by varying the off-take angles and the main channel flow rates consecutively. Four flow rates with corresponding flow depths of 16cm, 17cm, 18cm and 19cm were established and represented by Q_{16}, Q_{17}, Q_{18}, and Q_{19} respectively. The flow depths corresponding to each of the flow rates were established and marked on the walls of the main channel as bench marks to ascertain each of the required flow rates. The water in the sump was pumped to the elevated tanks that supplied water to the channel at controlled rates in line with the established bench marks while the weir and spillway provided at the downstream section maintained the required water level in the main channel.

Some light weight materials that could be used for the study of suspended sediment transport in rivers and streams such as polystyrene coal, bake lite, wood sawdust, polystyrol, Plexiglas, PVC, diatomaleous earth, natural sand, rice husk and silt have been recommended (Matondo and Skolersik, 1985; Obasi, 1988). The sediment material used in this study was silt from clay material with a size range of 0.053 – 0.064mm diameter and fall velocity of 0.0037m/s.

About 500 grams of silt materials were weighed out and added into a small bath with a litre of water and was stirred properly before being introduced at the beginning of the main channel. This was done after one of the desired main channel flow rates has been established by allowing the water level to rise to the specified reference point. In each case, the main channel flow rate and the sediment concentration were kept constant while the off-take angles were varied. At a given time interval, samples were collected with plastic containers at different locations including the upstream of the bifurcation, bifurcation point, off-take channel and downstream of the bifurcation for each of the off-take angles (30^o, 45^o, 60^o and 90^o) considered. About 50mls each of these samples were measured out in beakers for every experiment performed. The beakers were weighed while empty and thereafter weighed with the samples before oven dried at a temperature of 103^{o}C – 105^{o}C for twenty four hours. The samples were also reweighed after oven dried to determine the total solids which were analyzed in accordance with the standard methods for examination of Water and Waste Water (Apha et al., 1992) and the results obtained were recorded as presented in Table 1.

Table 1: Measured and predicted sediment distribution ratios at concave channel bifurcation

Θ	Q_{16}			Q_{17}			Q_{18}			Q_{19}		
	M	M(S_3)	P(S_3)	M	M(S_3)	P(S_3)	M	M(S_3)	P(S_3)	M	M(S_3)	P(S_3)
	q_1/q_3	S_1/S_3	S_1/S_3	q_1/q_3	S_1/S_3	S_1/S_3	q_1/q_3	S_1/S_3	S_1/S_3	q_1/q_3	S_1/S_3	S_1/S_3
30^0	1.79	2.95	3.03	1.15	1.78	2.92	0.76	1.40	2.3	0.56	1.21	1.89
45^0	1.49	2.66	2.48	0.86	1.50	1.81	0.61	1.20	1.48	0.47	0.95	1.28
60^0	1.23	1.50	1.38	0.72	1.07	1.26	0.54	0.97	1.07	0.40	0.75	0.9
90^0	0.84	1.20	0.99	0.60	0.91	0.81	0.41	0.79	0.66	0.32	0.65	0.57

Formulation of Empirical sediment yield Equations.

Tarekul Islam et al (1997) in their investigative studies established an empirical expression for sediment distribution at channel bifurcation, thus:

$$S_1/S_2 = M\,(q_1/q_2)^k \quad \ldots\ldots 1$$

In the present study, the authors have proposed some equations relating the off-take sediment concentration with the bifurcation angles and specific discharge ratios in the form thus:

$$S_1/S_3 = a_1\,\theta^{a2}\,(q_1/q_3)^{a3} \quad \ldots\ldots 2$$

However, introducing the log and semi log to linearize equation 2 would yield equations 3 – 5, thus:

$$\text{Log } S_1/S_3 = a_1\,\theta^{a2}\,(q_1/q_3)^{a3} \quad \ldots\ldots 3$$

$$S_1/S_3 = \text{Log } [a_1\,\theta^{a2}\,(q_1/q_3)^{a3}] \quad \ldots\ldots 4$$

$$\text{Log } (S_1/S_3) = \text{Log } [a_1\,\theta^{a2}\,(q_1/q_3)^{a3}] \quad \ldots\ldots 5$$

Where α_1, α_2, and α_3 are constants.

Table 2: Empirical equations for sediment distribution at concave channel bifurcation

S/No	Proposed Model Equations	Coefficients			Regression Coeff. (R).	Standard Error
		α_1	α_2	α_3		
1.0	$\text{Log}\,(S_1/S_3) = \alpha_1\,\theta^{\alpha_2}\,(q_1/q_3)^{\alpha_3}$	0.180104	-0.005573	0.258811	0.98884	0.03974
2.0	$(S_1/S_3) = \text{Log}\,(\alpha_1\,\theta^{\alpha_2}\,(q_1/q_3)^{\alpha_3})$	4.736665	-0.8199521	2.125059	0.95680	0.23792
3.0	$(S_1/S_3) = \alpha_1\,\theta^{\alpha_2}\,(q_1/q_3)^{\alpha_3}$	1.581895	-0.819952	0.573933	0.99434	0.02834

Results and Discussion

The data obtained from the experimental work carried out were used for the multiple regression analysis to ascertain the nature and degree of relationship existing between the selected parameters and the sediment distribution ratios in each of the proposed empirical equations. The regression model constants α_1, α_2, and α_3 were determined through simulation process by using the SPSS + PC statistical package and the results obtained from each of the proposed equations are presented in Table 2. The values of these constants are interpreted and substituted as shown in equations 6 – 8.

$$\text{Log}\ (S_1/S_3) = (0.1801(q_1/q_3)^{0.259})/(\theta^{0.0056}) \quad \ldots\ldots\ldots\ldots \quad 6$$

$$S_1/S_3 = \text{Log}\ [(4.74\ (q_1/q_3)^{2.13})/(\theta^{0.82})] \quad \ldots\ldots\ldots\ldots \quad 7$$

$$(S_1/S_3) = [(1.582\ (q_1/q_3)^{0.574})/(\theta^{0.82})] \quad \ldots\ldots\ldots\ldots \quad 8$$

Equations 6 – 8 are for the prediction of suspended sediment distribution pattern at concave channel bifurcation. These equations explicitly indicate that the sediment distribution ratios are proportional to the specific discharge ratios and inversely proportional to the off-take angles. The proposed expressions gave values of correlation coefficients from 0.95680 – 0.99434 with standard error values from 0.02834 – 0.23792. Equation (8) with log on both sides produced the highest correlation coefficient value of 0.99434 with a corresponding standard error value of 0.02834 while equation (6) with log on the left hand side of the equation yielded the second highest correlation coefficient value of 0.98884 with standard error value of 0.03974. Equally, equation (7) with log on the right hand side of the equation had the least value of correlation coefficient of 0.95680 with a standard error value of 0.23792.

Fig. 2a depicts the effect of discharge on the sediment distribution ratios as obtained from the experimental works conducted. It could be seen from Fig. 2a that the slopes of the plots of the sediment ratios against the off-take angles decrease with increase in main channel discharge. This implies that an increase in the main channel discharge will substantially increase the off-take discharge and consequently increases the off-take sediment concentration. For instance, the off-take angle of 60^o with main channel flow rates of Q_{16}, Q_{17}, Q_{18} and Q_{19} yielded off-take sediment values of $0.67S_1$, $0.94S_1$, $1.03S_1$ and $1.33S_1$ respectively. These off-take sediment concentration values indicate that the minimum main channel flow rate of Q_{16} yielded the minimum off-take sediment concentration values while Q_{19} which was the maximum main channel flow rate yielded the maximum off-take sediment concentration values for each of the off-take angles considered. This agrees with the previous studies (Obasi et al, 2008) which indicated that the increase in main channel discharge resulted equally in an increase in the off-take discharge which has probably influenced the off-take sediment intake due to high velocity of flow. In addition, Asselman, (2000) in his work found that the transportation of substantial sediment load usually vary as a function of the discharge rate.

Table 2 shows that virtually all the proposed predicting equations produced very high values of correlation coefficients in the multiple regression analysis carried out. However equation (8) with the highest correlation coefficient gave off-take sediment values that are close to those obtained from the experimental work. Fig. 2b shows the effect of discharge on the sediment distribution using data obtained from the evaluation of equation 8 which has the same trend as shown in Fig. 2a in the sense that the slopes of the plots of the sediment ratios against the off-take angles were decreasing with increase in main channel discharges. Conversely, the consideration of the off-take angle of 60^o with main channel flow rates of Q_{16}, Q_{17}, Q_{18} and Q_{19}, yielded off-take sediment concentration values of 0.73S_1, 0.79S_1, 0.94S_1 and 1.11S_1 respectively.

The relationship shown in Figs. 2a and 2b equally indicate that the sediment delivered to the tributary channels increased with increase in off-take angles for any of the main channel flow rates considered.

The sediment distribution pattern depicts that for any of the main channel flow rates considered, the tributary channels at 30^o off-take angle received the minimum sediment concentration values while those at 90^o off-take angle received the maximum sediment concentration values.

The result of the physical models conducted by Bulle (1926), Raid, (1961), Den Dekker and Vorthuizen (1994), Fokkink and Wang (1993) and Islam (2000) emphasized that sediment distribution is generally linearly related to the discharge distribution. In other words, the higher diverting angle attracts more suspended sediment load and is proportional to the discharge distribution or the sediment distribution is a function of the discharge distribution.

The result of the experimental studies on sediment distribution at concave channel bifurcation for the main channel flow rate of Q_{16} indicates that about 34% of the main channel sediment concentration entered the channel bifurcating at 30^o off-take angle while about 38% of the main channel sediment concentration entered the channel branching at 45^o off-take angle. Similarly, the branching channel at 60^o off-take angle received about 67% of the main channel sediment concentration while about 83% of the main channel sediment concentration entered the branching channel at 90^o off-take angle. The difference in sediment values delivered to tributary channels at off-take angles of 30^o and 45^o is about 10.5% while those of 45^o and 60^o is 43%. The tributary channels at 60^o and 90^o off-take angles have a difference of about 19.3% of sediment values received.

Similarly, the results of the values obtained from the predicting equation for various off-take angles indicate that about 33% of the main channel sediment concentration would enter the tributary channel at 30^o off-take angle while about 40% would be delivered at 45^o off-take angle. Correspondingly, about 73% of the main channel sediment concentration would enter the branching channel at 60^o off-take angle while about 100% would enter the off-take channel at 90^o off-take angle. It seems that at higher off-take angles virtually all the main channel sediment concentration will be delivered to the tributary channels. Figs. 4 - 7 generally show that the predicting equation under estimated the tributary channel sediment yield for off-take angles between 30^o – 70^o while for those between 70^o - 90^o the sediment values were over estimated for all the main channel flow rates considered. The predicting tributary sediment values equaled the experimental values at the off-take angles of 50^o – 70^o but varied for the various main channel flow rates.

The difference in sediment values delivered to the tributary channels using the predicting equation at off-take angles of 30^o and 45^o is about 17.5% while those of 45^o and 60^o is 45%. The tributary channels at 60^o and 90^o off-take angles have a difference of about 27% of the sediment values received.

Vershney et al. (1988) proposed that for the control of excessive silt entry into the off take channel, an off take angle of 60^o – 80^o should be considered suitable which is in disagreement with the results of the current study. The studies of Bulle et al. (1926) show that more than 90% of transported matter enters the diversion canal branching off at a conventional angle of between 30^o – 90^o from the main water course, but with about half of the original discharge. According to Bulle (1926) the variation of silt quantities with diverted flow showed that a balance (50-50%) distribution of silt attained only if some 25% of the original discharge is allowed to enter the canal. If the discharge carried by the diversion canal exceeds 60%, the entire silt load enters the off take canal. **He concluded by saying that the size of the optimum intake angle increases as the diversion ratio decreases.** Habermass (1935) recommended in his work that off-takes be located towards the downstream of the concave section for minimum sediment entering the off-take canal. However, it was observed that he was arbitrary sitting the off-take locations without considering the influence of the off-take angles and variation in main channel discharge. This suggests that the off-take angles to a large extent influenced the sediment delivery to the tributary channel at concave channel bifurcations.

For intakes in bends, the decrease in the strength of secondary currents would lead to the increase in the sediments delivered Randkivi (1993) or Novak et al (1990).

Conclusion

Results of both the experimental works and predicting equation on the off-take sediment distribution at the concave channel bifurcation reveal that the minimum main channel flow rate of Q_{16} yielded the minimum off-take sediment concentration values while Q_{19} which was the maximum main channel flow rate yielded the maximum off-take sediment concentration values for the off-take angles considered. The sediment distribution pattern equally depicts that for any of the main channel flow rates considered, the tributary channels at 30^o off-take angles received the minimum sediment concentration values while those at 90^o off-take angles received the maximum sediment concentration values for both the experimental study and predicting equation. It was observed that the predicting equation under estimated the tributary channel sediment yield for off-take angles between 30^o – 70^o and for those between 70^o - 90^o the sediment values were over estimated for all the main channel flow rates considered. The predicting tributary sediment values equaled the experimental values at the off-take angles of 50^o – 70^o but varied differently for each of the main channel flow rates. It could be seen from the various off-take angles considered that the divergence in results obtained from the experimental works and predicting equation is in the range of 2.9% - 17.8% for minimum main channel flow rate and 12% - 36% for maximum main channel flow rate suggesting that the predicting equation could be useful in the evaluation of sediment yield at concave channel bifurcation.

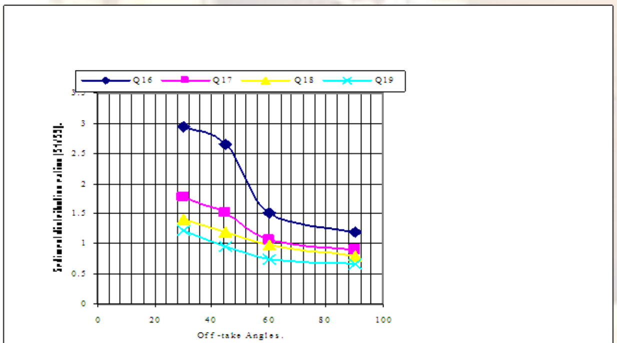

Fig.2a: Effect of off-take angles on sediment distribution(measured S3).

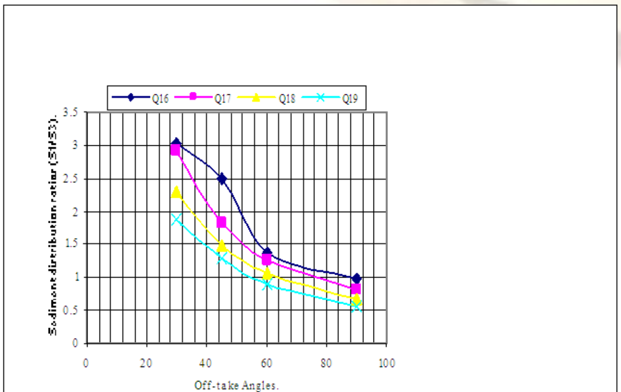

Fig.2b: Effect of off-take angles on sediment distribution (predicted S3).

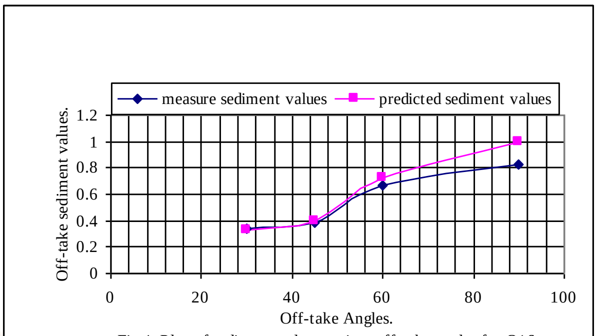

Fig.4: Plot of sediment values against off-take angles for Q16.

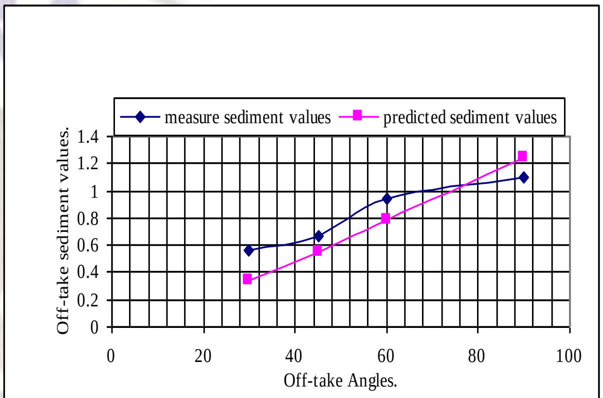

Fig.5: Plot of sediment values against off-take angles for Q17.

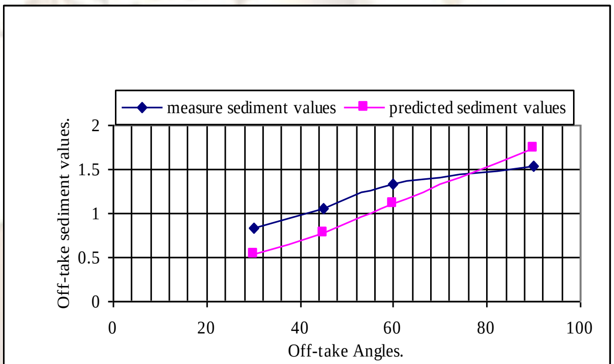

Fig.6: Plot of sediment values against off-take angles for Q18.

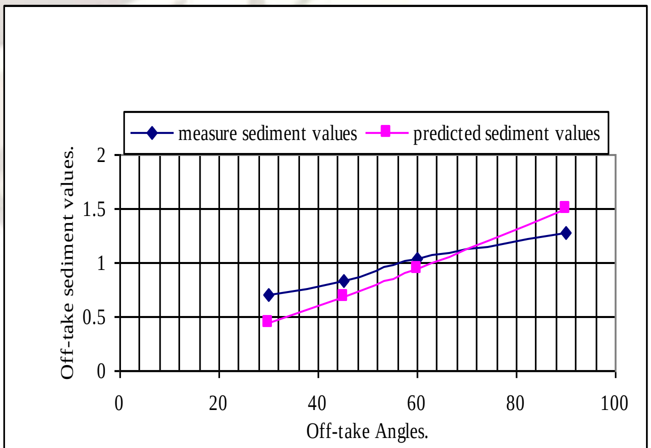

Fig.7: Plot of sediment values against off-take angles for Q19.

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