Three-Dimensional Simulation of Fluvial Environments

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Abstract : The study is to simulate a straight channel of the Arkansas river around Tulsa, Oklahoma, USA, which channel underwent massive erosion and channel migration as it returned to a more natural, meandering path. Experiments have done by modeling the sedimentary processes that changed in response to changing hydraulic and geologic parameters resulting from the excavation of the channel. Geologic parameters such as fluid and sediment discharge, velocity, transport capacity, and sediment load are input into the model. These parameters regulate the frequency distribution and sizes of sediment grains that are eroded, transported and deposited. The experiments compare favourably with aerial photographs, recreating similar patterns of fluid flow and sedimentation. Comparisons reveal a substantial degree of concordance between actual and simulated channels. It is to help validate the simulation procedure's general applicability for experiments involving flow and sediment transport by rivers. Moreover, simulations provide insight for understanding and spatial distribution of sediment bodies in fluvial deposits and the internal sedimentary structure of fluvial reservoirs. This simulation model can be contributed to support the development of the new design criteria compatible with natural river processes including flood, especially drainage problem to minimize environmental disruption.

Key Words : Fluvial Environments, Arkansas River, Channel Underwent Erosion, Channel Migration, Excavation of Channel, Minimize Environmental Disruption

Introduction

The river flow and river basin have been existed always and related closely to our life, however, the interactions between them are poorly understood. The reasons are river flow may be steady or unsteady, and may change complicatedly with time and space. A series of rapid changes in the Arkansas River near Tulsa, Oklahoma, U.S.A that stemmed from engineering work provided an excellent opportunity to relate changes in channels to changes in river flow. In 1966, the U.S. Army Corps of Engineers dredged a long, gently curving channel to form a tailrace downstream from Keystone Dam, within a segment of river about 12km long, replacing the network of natural channels that formerly existed there. Keystone Dam was completed as part of the plan to transform the Arkansas River into a navigable waterway. In 1967, a year after its construction, a major flood totally destroyed the dredged channel, and the river began to reverted to its old general form of complex, shallow channels. Changes during and following the dredging were

monitored with aerial photographs each year from 1966 to 1969 (Fig. 1) and were used to map changes in channels during this period.

Fig. 1. Chronological aerial photographs of Arkansas River around research area near Tulsa, Oklahoma from 1966 to 1969. Photographs show the migration of river at downstream of Keystone Dam. The arrow represented the location where the channel migrated toward inner side of channel curvature.

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The experiments were run with "Modified SEDSIM", the name SEDSIM being an acronym for SEDimentary basin SIMulation. SEDSIM consists of an aggregation of inter linked computer programs that collectively simulate the major processes that create and modify sedimentary basins. The basic treatment of flow and sediment transport is described in detail by Tetzlaff and Harbaugh (1989). This three-dimensional computer simulation model can simulate basic elements involved in the formation of alluvial and delta environments, including erosion, transport, and deposition that are coincident with fluid movement. Those components of SEDSIM relevant to flow and sediment transport in open channels and their graphic display were employed. This is also a dynamic model that can simulate the evolution of sedimentary environments through time. It can be used to gain understanding about modern environments, and can also be used to recreate ancient environments whose histories are preserved in the stratigraphic record. Because SEDSIM simulates erosional as well as depositional events, it is particularly valuable in studying stratigraphic sequences that include significant periods of hiatus or periods of non-deposition, where modern analogs are often insufficient.

The excellent and the detail geological survey for channelization was done in a tailrace downstream from Keystone Dam before 1966, and the survey was documented. The documentations of the geological and hydrological survey were used to rebuild the river basin of the downstream from Keystone Dam at 1966. This documentations with sequential aerial photographs showing the changes in the channels suggested that this segment of the Arkansas River would be appropriate for a series of simulation experiments in which various river flow rates would be supplied, and its response observed over a period of several simulated years. The objective of this research was to approximate the river's actual behaviour to a reasonable degree, to predict the changes in river, and to help validate the simulation procedure's general applicability for experiments involving flow and sediment transport by rivers. It is presented here a series of computer sensitivity experiments in which the channel migration showing meandering are changed systematically with daily river discharge.

The results of the experiments are hypothetical reconstructions with filling water in channel that can be compared with aerial photographs, thus enhancing our understanding of the river systems.

The Model Brief

The sedimentary basin simulation model, developed in Stanford University (Tetzlaff and Harbaugh, 1989), describes open channel flow or the combination of fresh water and sea water flow, and sedimentary deposits that it creates are related to the transport of sediments by flow. The model was modified for stability of numerical analysis, for representation of effective and accurate sediment aggregation, and for fluvial environments, especially using daily river discharge. The basic hydrodynamic equations is adaptations of the Navier-Stokes equations which combine the continuity equation and the momentum equation to provide a complete mathematical description of flow for an isotropic Newtonian fluid whose properties are uniform in all directions and which follows Newton's laws of motion (Table 1; see Table 2 for variable definitions). The Navier-Stokes equations in Table 1 are simplified forms for fluid flow, derived under the following assumptions: (a) the fluid is homogeneous and incompressible at constant temperature, (b) the fluid density and viscosity are constant, (c) the Coriolis acceleration is negligible, (d) the pressure distribution is hydrostatic, (e) the profile of fluid velocity is constant. The constant velocity profile assumption implies there is no shear in any horizontal plane in the flow. Thus horizontal friction is absent within the flow. The numerical approach, however, reintroduces friction to model the flow's behaviour more realistically and also reintroduces the effect of shear between portions of fluid of different horizontal velocities. These equations contain parameters that depend partly on flow conditions which are related to factors that include channel shape, flow depth, slope of the water's surface, and flow velocity. The numerical representation of the Navier-Stokes equations employs a "marker-in-cell" procedure in pseudo-three dimensions, in which the flow velocity and the position of each fluid element is represented at specific geographic point during each time increment. By means of a two-dimensional grid of square cells, the depth

Table 1. Hydrodynamic and sediment transporting equations for sedimentary processes in fluvial environments

Continuity Equation of fluid	
$\frac{\partial u}{\partial y} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$	
<i>X-dir</i> Momentum Equation of fluid	
$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\mu}{\rho} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)$	
<i>Y-dir</i> Momentum Equation of fluid	
$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\mu}{\rho} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right)$	
Sediment Continuity Equation for single grain-size	
$h \frac{Ds}{Dt} = -\frac{\partial Z}{\partial t}$	
Sediment Transportation Equation for single grain-size	
$h \frac{Ds}{Dt} = f \{Q, \nabla H, \nabla Z, s, F\}$	

Table 2. Variable definitions in the simulation model

<i>h</i>	= water depth
<i>p</i>	= pressure
<i>s</i>	= volumetric sediment concentration
<i>t</i>	= time (s)
<i>x, y, z</i>	= Cartesian coordinates
<i>u, v, w</i>	= respective components of velocity
<i>μ</i>	= fluid viscosity
<i>ρ</i>	= fluid density
<i>D</i>	= derivative in the direction of flow
<i>F</i>	= array of coefficient defining sediment properties
<i>H</i>	= flow surface elevation with respect to sea level
<i>Q</i>	= horizontal flow velocity
<i>Z</i>	= topographic elevation with respect to sea level

of flow is represented in each cell, as well as the average velocity of fluid elements in the cell, the second derivative of velocity in the cell, and the topographic elevation at the bottom of the channel in the cell. The marker-in-cell procedure is suitable for simulating free surface flow under a variety of different flow conditions.

The marker-in-cell technique which was first described by Harlow (1965) and involves a grid divided into cells. Markers are placed in those cells which initially contain fluid, with typically 10-20 markers evenly distributed within each cell. The adaptation of the marker-in-cell procedure uses relatively few markers, and represents flow depths with an “area-weighting” and flow in continuous form (Fig. 2). Other improvements correct for local boundary conditions and assign fluid element volumes to represent water surfaces that accord appropriately with submerged topography (Fig. 3). For example, flowlines in a straight

Fig. 2. (A) Diagram showing fluid information assigns the nearest node point
(B) Diagram showing area-weighting scheme, which was newly developed for reducing the numerical errors

Fig. 3. Diagram showing the correct assignment of fluid depth due to topographic effects and how to overcome the numerical error of the fluid depth assigned which frequently happens in channel flow

Fig. 4. Comparison the results of the fluid flow obtained from different numerical methods.

- (A) Diagram showing the numerical error of the fluid movement using the concept of the old version of SEDSIM.
- (B) Diagram showing the correct fluid movement using the concept of the modified marker-in-cell method.
- (C) Diagram showing the correct slope of the fluid surface using the concept of the continuous flow.

channel with constant slope should be straight and not curving. Fig. 4 schematically shows flow before and after improvement of the code. Therefore, the modified model is newly developed the condition of fluid body and the boundary condition, which overcomes the numerical errors and increases the numerical accuracy.

The model transports clastic sediment in flows, and can accommodate up to four grain sizes. Sediment transport is represented with a sediment continuity equation and a transport equation that is a modified version of the Meyer-Peter and Muller (1948) equation (Table 1 and 2). The sediment continuity equation ensures that all sediment that is eroded, transported, or deposited is properly accounted for, and the sediment transport equation calculated how much sediment of each grain size that is available for transport will be transported by a flow of given hydraulic characteristics, including the rate at which sediment is transferred between the flow and the underlying bed. The model represents the total sediment load as a single component, although the load consists of both bed load and suspended load. However, the model reintroduced the empirical relation-

ship of fall velocities of sediments to have same effects that the total load consists of both bed load and suspended load. The transport of sediment depends on the balance between the flow's transport capacity and the effective sediment concentration in the flow. Also the deposition or the erosion depends on the transport capacity of the flow and whether critical shear stresses for grain sizes present at the water-sediment interface have been reached or exceeded. To represent deposited sediment, the model utilizes three-dimensional cells that contain specific volumes and types of sediments assigned to them during successive time intervals during which deposition or erosion, or both may have occurred. Detailed accounting procedures deal with topographic changes caused by erosion or deposition as determined by changes in sediment load. The accounting scheme also retains a history of depositional and erosional events. Sediment deposited in "sediment cells" represented in four-dimensional arrays permits an evolving, three-dimensional stratigraphic record to be maintained. These accounting procedures are part of model's ability to represent sorting and differential transport of sediment.

Experiments involving the fluvial environments, especially river, incorporate varying discharge rates, which in turn affect fluid depth, fluid volume, fluid velocity, total sediment load, sediment load composition, and transport capacity. By contrast, earlier versions of SEDSIM permitted input of only a constant fluid discharge rate. Sediment carried by river has a wider distribution of grain sizes than the range for which the model was originally designed and calibrated, especially the coarser grain sizes, requiring adjustments in estimating the particle fall velocities which the empirical relationship of Colby (1964) was extended.

Application of The Model

The Study Site and the Depositional Change in River

The study area is located about 27 km west of Tulsa and involves about 5 km of the valley's length (Fig. 5) containing the dredged channel that was to serve as the tailrace for Keystone Dam constructed by the U.S. Army Corps of Engineers. In the study area, the Arkansas River occupies a valley about a kilometer wide on average. Upstream, the river has a

Fig. 5. Location of study area on Arkansas River plain in Tulsa County, Oklahoma (U.S.A).

total drainage area of 193,000 km², part of which ordinarily contributes only minor volumes of flow. The main contributing drainage area spans about 58,000 km² (Corps of Engr., 1965). Sediment forming the alluvial fill in the study area before construction of the dam consisted mostly of medium and coarse sand, although sediment of smaller grain sizes was also present. Bed-rock consists of the Chanute Formation of Late Pennsylvanian age that is composed of shale, siltstone, and fine grained sandstone (Steinmetz, 1967). Data for the period from 1966 to 1969 relevant to the study area include aerial photographs, daily river discharge and river stage records from November 29, 1966 to March 25, 1969, geologic logs of 35 boreholes that penetrate the alluvium as it existed in 1965, and a detailed topographic map of the river channel for 1965, all of which were provided by U.S. Army Corps of Engineers at the Keystone Dam Office. Data of sieve analysis and sediment load according to river discharge rate was reanalyzed by statistical tool like the least square method.

The sequential aerial photographs show large changes in channel patterns and widths between 1966 and 1969. Migrations of channels and channel shapes can be linked with not only sedimentary processes but also flow volume in river. The dredged channel was destroyed by the 1967 flood, following which lateral bars formed that were arranged alternately along the channel's banks. During three years from

1967 to 1969, the channel continued to migrate and to form meandering river. The channel migrations during three years for experimental duration reveal an unusual feature. At the inner side of a river bend, deposition usually forms a point bar, while the outer side of the bend is eroded. In the study area, however, the aerial photos document that the channel depositing a point bar but then quickly reversed its direction so that the point bar was eroded in three year period. It is possible that the river dynamically re-established its former bed. A key point of this study was to determine whether the simulated river would exhibit generally similar behaviour. In 1969 the channel seemingly returned more or less to its "natural" state, but a succession of two floods, one in 1967 and the other in 1969, with maximum discharge rates 736 m³/sec and 849 m³/sec, respectively, created temporary changes. The maximum discharge in the 1969 flood was about four times larger than the average discharge of 187 m³/sec observed during the previous 41 years (Steinmetz, 1967).

Input Data for the Simulation Model

The model used in early version was designed to basin scale for the occurrence of oil and gas in ancient deposits. Time scale was also used the geological time like the several thousand to million years. However, the model used in this application is relatively small scales of river channel and short time duration of three years, comparing the geologic concepts. Therefore, the model is to represent a river in an experiment, it must be supplied with information about the river discharge rate, its sediment discharge rate including the proportions of different sediment grain sizes that form flood plain, the channel depths and other aspects of the topography of the alluvial fill over which the river flows at the outset of the experiment, and the composition of the alluvial materials that forms the fill at the outset of experiment. Other information also must be supplied to control the experiment, such as the length of the discrete time step for which the numerical solutions for flow equations are updated, and the simulated span of time that the experiment is to represent. The responses obtained in experiments stem entirely from these assumptions supplied as input.

Daily river discharge rates for the period based

on measurements of releasing discharge at Keystone Dam of the Corps of Engineers are plotted in Fig. 6. Since flow velocities as one of initial conditions are needed, a relationship between depths and discharge rates locally relevant to the study area of the Arkansas River is required, and was obtained by analyzing statistically measurements of flow depth and discharge rates. The report informed by Corps of Engineers (1969) presents a succession of measurements of the maximum and minimum discharge rates of the river with the maximum river depths at Tulsa station for each month from January 1955 through December 1965. By plotting the succession of maximum discharge rates versus maximum river depths, the log-log plot reproduced in Fig. 7 was obtained, yielding an empirical relationship of observations to which lines were fitted by regression. By referring to this plot, or more specifically to the two linear equations that represent the two straight lines fitted to the observations, values for river depth that correspond to specific river dis-

charge values can be readily calculated. Similar observational data for the Arkansas River (Bradly, 1990) permit its river discharge rate to be plotted against sediment discharge rate, and an empirical relationship to be shown by fitted lines (Fig. 8).

Since one of the boundary conditions at the outset of each experiment involved the state of the river's alluvial fill, it was necessary to represent the fill's topographic form and its sedimentological composition in full three dimensions. Information that permitted the reconstruction of the alluvial fill was provided by geologic logs of sediment encountered in the 35 boreholes that penetrated the alluvium in 1965. Fig. 9 shows their locations in the study area and Fig. 10(A) shows an example log (Corps of Engr., 1968). The boreholes were logged by examining the samples obtained as the holes were drilled. The scheme for describing the sample composition is qualitative and is an adaptation of the "unified soil classification system" procedure (Lambe and Whitman, 1979). Different types of alluvial material were classified according to the scheme listed in Table 3, and given letter designations shown there, as adapted from the unified soil classification procedure. The quantitative measures of sediment proportions are required as one of the initial conditions. More accurate initial condition of sediments in river simulates better the experiment results like real sedimentation. Because the sedimentary processes of both erosion and deposition are represented various results with different sediment composition of river basin. It is necessary to convert qualitative designations of the borehole logs, to an arbitrary numerical scheme in which the different types of sediment that

Fig. 6. The daily discharge rates reported at Keystone Dam during November 19, 1966 to March 25, 1969

Fig. 7. Relationship between discharge rate and Arkansas River depth at Tulsa, Oklahoma

Fig. 8. Plot of discharge rate and sediment load in Arkansas River at Tulsa, Oklahoma.

Table 3. Classification used in descriptions of logs of bore-hole in alluvium

Group Symbols	Typical Names
GW	Well graded gravels, gravel-sand mixtures, little or no fines
GP	Poorly graded gravels, gravel-sand mixtures, little or no fines
GM	Silty gravels, poorly graded gravel-sand-clay mixtures
SW	Well graded sands, gravelly sands, little or no fines
SP	Poorly graded sands, gravelly sands, little or no fines
SM	Silty sands, poorly graded sand-clay mixtures
SC	Clayey sands, poorly graded sand-clay mixtures
ML	Inorganic silts and very fine sands, rock flow, silty or clayey fine sands with slight plasticity
CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
OL	Organic silts and organic silt-clays of low plasticity
MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
CH	Inorganic clays of high plasticity, fat clays
OH	Organic clays of medium to high plasticity

formed the alluvium were given integer value, thus placing them in semi-quantitative form. These integers then were later transformed into proportions of sediment of specified sediment-grain diameters. The succession of transformation is illustrated in Table 3, Table 4 and Fig. 10. Information from the borehole logs transformed to the semi-quantitative estimates was supplied to a three dimensional space fitting procedure known as Stratamodel (its commercial name).

Table 4. Numbers assigned using descriptions of geological logs and unified soil classification

Soil Symbols	Assigned Number
SP or SW with GW, GP, GM, or GC	1
SP or SW	2
SP or SW with SM	3
SM	4
SC	5
ML, CL, OL, MH, CH, or OH	6

Fig. 9. Map showing the locations of the 35 geological logs, used for three dimensional reconstruction of the alluvial fill in study area

Fig. 10. Diagrams showing the conversion from geologic log to numerical data in which the different types of sediment that formed three dimensionally the alluvial fill.

Table 5. Sediment ratio in each sediment cell which has average composition

Average assigned number	Sediment Composition (%)			
	Gravelly Sand (>0.5mm)	Medium Sand (0.25–0.5mm)	Fine Sand (0.063–0.25mm)	Silt and Clay (<0.063mm)
1.0–1.3	12	60	25	3
1.3–1.8	8	55	31	6
1.8–2.3	4	50	36	10
2.3–2.8	3	45	37	15
2.8–3.3	2	40	38	20
3.3–3.8	1	35	41	23
>3.8	1	30	44	25

In turn, Stratamodel generated a three dimensional numerical grid of sediment compositional information, still using the arbitrary semi-quantitative numerical scheme. At each grid node in the three dimensional grid, Stratamodel interpolated a semi-quantitative value. The next task was to transform the arbitrary values into proportions of four sediment types of specified grain diameters, using the classification in Table 5. A special computer program was devised to do this, and the information in the requisite form was then supplied as part of the input for each experiment. This information represents the geometric form and sedimentary composition of the alluvial fill in the study area as it is presumed to have existed at approximately the outset of the span of time represented in the experiments. All of the experiments are presumed to begin on November 29, 1966, the date that the aerial photographs were taken in that year and arbitrarily selected for the outset of the experiments. This assumption can almost be accurate information, because the sediments in flood plain can not exchange within short terms like one or two months, not as the flood occurs.

The channel's topographic form in 1966 was also required as an aspect of the alluvial bed at the outset of the experiments. A detailed topographic map (1:5,000) produced by the Corps of Engineers was utilized. Elevations from the map were digitized at locations on a grid containing 326 columns and 92 rows, defining 19,992 square cells. Each cell is 15 by 15 m in extent, so that the grid encompasses an area 4,875 m long and 1,365 m wide, providing a level of detail and an area expanse sufficient for observing simulated responses in experiments. The topography of the bedrock on which the alluvial fill rests was also required,

and it was produced by combining information from the detailed topographic map and the 35 boreholes. The bedrock topography was presumed to represent a basement that was resistant to erosion and remained unchanged during experiments. Also the extension of basement was arbitrarily arranged the outside of flood plain, because the outside area of flood plain was not related to sedimentary processes.

Flow velocities were required, and they were obtained from observed river discharge rates measured on a daily basis. To calculate flow velocities from discharge rates, it is necessary to know fluid depths because fluid velocity is inversely related to cross sectional area of flow. For example, for a given discharge rate, the velocity is higher in a narrow or shallow channel than in a wide or deep channel. Thus, if the water filled area of vertical section and discharge rate are known, flow velocity can be calculated. Channel widths can be determined from the detailed topographic map (Corps of Engr., 1965) and channel depths can be determined from the relationship between the Arkansas river stages (Steinmetz, 1967) and discharge rates. Fig. 6 presents daily discharge rates estimated at Keystone Dam from November 1966 to March 1969, and Fig. 7 provides an empirical relationship between depth and discharge rate. The empirical relationship may be expressed by two lines fitted by regression whose equations are

$$D_f = \begin{cases} \text{Exp}(-2.37 + 0.43 \ln Q) & Q > 84.4 \text{ m}^3/\text{sec} \\ \text{Exp}(-0.16 + 0.16 \ln Q) & Q < 84.4 \text{ m}^3/\text{sec} \end{cases} \quad (1)$$

where D_f is fluid depth in meter and Q is discharge rate in m^3/sec .

In simulation experiments, initial conditions consisting of discharge rates, flow velocities, sediment load and grain size transported by water must be provided. The boundary conditions to be provided are topographic shape of study area, sediment composition of flood plain in three dimension. Flow volume is provided in the form of fluid elements that enter the simulated system. Specific unit volume of fluid element is calculated with velocities in two dimension from discharge rate. In the experiments, the volume of each fluid element was set at 67.5 m^3 . The numbers of fluid elements supplied per unit time can be set so that it corresponds with the Arkansas River's observed discharge rates, providing the link between

observations on the actual river and inputs to model simulations. In experiments, the locations at which fluid elements enter the simulated area are coincident at starting profile of river in study area. Therefore, river flows into model area as many fluid elements, which represent exact same amount of river volume at a every moment. The volume of a fluid element and the rate at which the fluid elements are supplied represent the fluid discharge rate. Since the discharge rate was varied each day, the following procedure was used:

1. A "source" location in mode was selected for the input of fluid. This location consists of a vertical section through the channel parallel to the x direction. The location of the source is marked as a point (x, y coordinate) on map of the channel obtained in the simulations. The trace of the section representing the source location always remained fixed, but the form and depth of the channel in the section varied on a daily basis because of variations in the discharge rate and because erosion and deposition occurred there on an ongoing basis. The section representing the source location was more or less perpendicular to the long direction of the channel, but not perfectly so.

2. The water depth in the section was then calculated, based on observed relationships between water depth (river stage) and discharge rate (Fig. 7). Since the surface of the water in the channel is assumed to be level, the vertical area of the water-filled channel in the section is established. The channel represented in the section was divided into a grid composed of rectangular cells in which each cell was 15 m long (corresponding to the 15 m width of grid cells representing the simulated area in the horizontal plane) and 0.3 m high. Each cell represents a cross section through a fluid element. The selection for the height is arbitrary, but is a compromise between a smaller height or cell area (which provides greater accuracy) but requires more computing effort, and a larger height which would require less computing effort, but would lead to numerical instabilities such as flow uphill or excessively fast flows. It was determined as 0.3 m of height of fluid element, considering above facts.

3. The discharge rate is closely related to the area of the water-filled vertical section and flow velocity. For a given discharge rate and a given water-filled

area of vertical section, there is a given velocity. Discharge rate divided by water-filled area of vertical section equals velocity. Calculated velocity is its magnitude only, and flow direction is determined along main direction of river which is same as line along maximum depth of river. Since each fluid element represents a volume, the third dimension of each fluid element is defined by the velocity at the source section. The velocity calculated for the water-filled vertical section as whole is assigned to each fluid element. Therefore, the discharge rate supplied as input could be represented as the number of fluid element supplied per unit time. In practice inputs to model were represented in terms of cubic meters, which were converted to fluid elements internal to the program. The fluid (and sediment) supplied as input were always entered at the source, which are therefore initial conditions for the numerical solution of equations. Interestingly, the source is also a geographic boundary.

4. The sediment load is then calculated using the empirical relationships graphed in Fig. 8 that relates river discharge rate to total sediment load. The total load is then splitted equally among each cell in the water-filled vertical section at the source, so that the amount provided to each fluid element is obtained by dividing the total load moving through the water-filled vertical section per unit of time by the number of fluid elements moving through the section per unit time.

Sediment Load and Sediment Composition

In experiments, sediment load and sediment composition also must be specified. Sediment composition is expressed by ratios of up to four types of clastic sediment. The types are defined in terms of sediment clastic of specific grain diameters measured in millimeters. In a simulation experiment, most of the sediment represented will consist of a mixture of the four (or fewer) different types defined. Of course actual sediment generally consists of a continuous range of grain sizes, so that the specific grain sizes defined for a particular experiment provide only an approximation of an actual continuous range. In spite of this simplification, model performs well. The use of maximum of four specified grain diameters represents a simplification from a computer programming stand-

point, and helps reduce computer running times in experiments. When sediment is transported, the quantity transported depends on the balance between the flow’s transport capacity and the effective sediment concentration in the flow. For example, if the sediment concentration is less than the transport capacity and the critical shear stress is exceeded, erosion occurs. If the sediment concentration is more than the transport capacity, deposition occurs.

Empirical relationships between fluid discharge rates and sediment load for the Arkansas River for the period from 1965 to 1970 are presented in Fig. 8. The original observational data is not shown in figure, but two straight lines were fitted by regression to the data by Bradley (1990). Equations for the lines are as follows :

$$Q_s = \begin{cases} \text{Exp} \left(-14.12 + 2.37 \ln Q \right) & \text{if } Q > 213.2 \text{ m}^3/\text{sec} \\ \text{Exp} \left(-1.90 + \ln Q \right) & \text{if } Q < 213.2 \text{ m}^3/\text{sec} \end{cases} \quad (2)$$

where Q_s is sediment load in kg/day, and Q is discharge rate in m^3/sec .

In experiments, the proportions of sediment of different grain sizes were arbitrarily assumed to be constant, with 10% of coarse sand, 60% of medium sand, 22% of fine sand, and 8% of combined silt and clay. The rationale for selection of these proportions is that calibrated the average composition of the body of alluvium in the study area based on the borehole logs transformed to proportions of four grain sizes (Fig. 10). According to Bradley’s survey (1990), the composition of sediment carried annually by the Arkansas River contains a high proportion of silt and clay. Those compositions are 10% of gravel and coarse sand transported as bed load, 27% of medium and fine sand, 57% of silt, and 6% of clay. During times of normal flow, most of the sediment transported by the

Fig. 11. Cumulative plots of grain-sizes based on sieve analysis for specific depths in alluvium of Arkansas River at six different boreholes

Arkansas River is trapped in Keystone Dam, with very little sediment entering the study area below the dam. Thus, sediments transported and redeposited by the river under those conditions is derived from the body of alluvium that pre-existed. Cumulative grain size distributions are shown Fig. 11, which based on sieve analysis for specific depths in body of alluvium at six different boreholes. As a compromise, the proportions of the four sediment sizes were arbitrarily chosen as listed above. This assumption represents a balance between the relatively high proportion of silt and clay carried overall by the river, and the higher proportion of sand in the body of alluvium below the dam.

Comparison of Results with
Geologic Observations

Initial Condition (November 29, 1966)

At the outset of the experiments in simulated 1966, it was necessary to supply the topography of the alluvial bed and its composition as they existed before the simulations were begun. The initial topography was adapted from the detailed topographic map provided by the Corps of Engineers (1965). The river channel was then filled with water so that its outline could be compared with aerial photographs taken in November 29, 1966. The aerial photographs outline the water-filled channel very clearly, permitting the digitized channel supplied as input to model to be compared readily with the actual channel (Fig. 12).

The filling of the channel with water was accomplished as follows: For any given discharge rate, the river stage or river depth was determined based on the ten-year record relating maximum discharge rates

Fig. 12. Comparison between the initial condition of experiment and aerial photograph at 1966. The channel was excavated within the river by the U.S. Army Corps of Engineers.

and maximum depths provided in Steinmetz's report (Fig. 7), which is based on the Corps of Engineers from 1956 through 1965. At a series of 326 sections through the river's channel, the elevation of the lowest point in the bottom of the channel was located, and the river's depth added to that elevation, giving an elevation for the surface of the water. Each section represents an individual row in the cellular grid, which spans 326 rows and 92 columns. The elevation of the water's surface was assumed to be uniform within each row of section. The series of sections generated in this manner yield the water-filled channel. At any point in the river, the difference between the elevation of the river's surface and the elevation of the river's bed is the depth at that point. Fig. 12 shows depth contours (as shades of grey) at the outset of experiments in 1966. Depth contours for subsequent years were generated with the same procedure, except that depths then represent changes in channels that stem from model's fluvial activities.

Representation of Time in the Simulation Model

The total span of time represented in the simulations extended from November 29, 1966 to March 25, 1969, a period of 849 days. Each simulation experiment would span the entire 849 days. For discussion purposes, it is convenient to separate this total period into three subperiods whose boundaries coincide with the dates when aerial photographs were taken. The first subperiod extends from November 29, 1966 to August 26, 1967, the second from August 26, 1967 to May 1, 1968, and the third from May 1, 1968 to March 25, 1969. During the total span of 849 days, for each simulated day, the model received as input the Arkansas River's discharge rate estimated for that day, based on outflow from the reservoir impounded by Keystone Dam. Fig. 6 shows variations on a daily basis of the discharge rates in this period. For comparison purposes, the simulated changes in the river's channel were compared with aerial photographs. The comparisons are not chronologically exact, but are sufficiently close. The overall span of 849 simulated days was divided into 20 arbitrary subintervals, each being 42.45 days in length. Comparisons with aerial photographs were made at the closest subinterval. For example, the span of time between the first and second set of aerial photo-

graphs is represented by approximately six subintervals, each of 42.45 days, for an aggregate of 254 days, which is reasonably close to the actual span of 270 days. Since the results of experiments represent the topographic and geologic condition in three dimensions and the river discharge was used its exact day's, the results of 16 days after would not be different from the results of photographed day.

The selection of a cycle and of an interval for updating the flow calculations of unit time, was based on the following considerations. The numerical solutions of the equations that represent flow by movement of fluid elements must be updated frequently if flow is to be approximated effectively. If an interval is much longer unit time, numerical instabilities in the flow tend to occur, such as fluid elements moving uphill or flowing too fast (Harbaugh, *et al.*, 1991). When an interval of 60 seconds was tried, the flow was unreasonably fast, and when 30 seconds was tried, the flow was sometimes too fast. When 10 seconds was tried, the results were satisfactory, and an interval of ten seconds was used subsequently. Updating of the flow equations at ten second intervals poses a large computational load. To economize on arithmetic, the flow parameters at the end of each ten second update were held constant for a span one hundred times longer, for a total interval of 1,000 seconds. During the span of 10 seconds in which the flow parameters are updated, the flow may erode, transport, or deposit clastic sediment. Erosion, transportation, and deposition take place within individual fluid elements. To extrapolate to a span of 1,000 seconds representing a cycle, the amount of erosion, transportation, and deposition in each fluid element during the ten second interval was multiplied by 100. The selection of extrapolation provides a reasonable interval for updating changes in the river's bed because changes in the amount of erosion, transportation, and deposition of sediment during that time were reasonably small, but of course erosion, transportation, and deposition continued to take place during the entire cycle, so that the overall changes in each cycle were reasonable. In experiments involving simulation of deltas, extrapolation factors of 100,000 were successfully employed (Harbaugh, *et al.*, 1991). The major difference to experiments of delta is large in the unit size of grid cells

of 250 m. By contrast, in river experiment, the unit size of grid cells were 15 m, requiring smaller extrapolation factor. Calculations suggest that if an extrapolation factor substantially greater than 100-fold had been used for this experiment, so that the slope of the river's bed where deposition occurred would be excessively great. Thus, an arbitrary extrapolation factor chosen in this experiment appeared to be reasonable.

Comparison during the First Sub period

(Nov. 1966 – Aug. 1967)

A substantial number of trial simulations were made before a more or less satisfactory final simulation experiment was obtained. About 100 trials were conducted, although most of them involved changes in the program. The parts of modification in program are fall velocities by grain sizes, comparing the amount of deposition. Since the input parameters to model were based on actual data, it was necessary to adapt the model programs themselves to accommodate the specific input requirements. The input parameters for each specific experiment consisted of (a) the initial topographic form of the river bed as of November 29, 1966, (b) the composition of the river bed based on logs of borehole drilled in 1965, (c) the river discharge rate for each day, (d) the sediment load as a constant proportion of discharge rate, and (e) the proportions of four types of sediment defined by particle diameters in the sediment load. An example input data for sediment composition is shown in Tables 3, 4, and 5. Internal to model programs, the following factors were calculated and updated during each cycle: (a) river depth, (b) velocity and position of each fluid element, (c) the sediment load of each fluid element, and (d) the composition of the sediment load in each fluid element.

In each experiment, the total span of simulated time was 849 days, representing the period from November 29, 1966 to March 25, 1969. During this total span of time, the changed input parameter was the river discharge rate. During the first subperiod, the discharge rates were relatively low from November 29, 1966 until June 19, 1967. The level of river is relatively low until June 19, 1967, but on June 20, a substantial flood began, reaching a peak on July 1, 1967. Changes in the channel for both the actual and the

Fig. 13. Comparison between the result of experiment and aerial photograph at 1967. The excavated channel was disrupted and migrated. The arrow represented the location where the channel migrated toward inner side of channel curvature.

simulated river during this subperiod are shown by comparing aerial photographs and computer plots. Fig. 12 shows the actual and simulated channels as of November 29, 1966. Although the simulated channel during the peak the flood of 722 m³/sec was obtained from the experiment, unfortunately it could not compare with aerial photograph which was not available for that date. Fig. 13 shows the actual channel on August 26, 1967 and the simulated channel at 254 days after the outset of the experiment.

Floods of June – August, 1967

The smoothly curving channel created by the Corps of Engineers was destroyed during the flood. The aerial photos of August 26, 1967 reveal no trace of the smooth channel, attesting to the power of the river in flood and exposing the naivete of the Corps of Engineers in constructing the channel in the first place. The smoothly curving channel was about 30 m wide, whereas the average width of the channel after the flood was about 90 m wide, and increase of roughly 30 fold. These estimates involve comparison of the aerial photographs of November 29, 1966 and August 26, 1967, but there are problems in the comparison because of the large difference in fluid discharge rate on the two dates. On November 29, 1966, the discharge rate was about 30 m³/sec, whereas on August 26, 1967, it was about 212 m³/sec, or 7 times greater. As a consequence, the channel appears wider in the August 26, 1967 photographs because the volume of water was greater then. In spite of this difference in water volume, the channel after the flood was wider.

The other major change was the development of meanders. The forms of the meanders are difficult to

describe in words, but the aerial photographs represent their forms quite effectively. One of the changes that is mildly surprising involves lateral shifting of the channel at the point marked with an arrow in Fig. 13. The channel migrated toward the concave side of the smoothly curving channel (toward the south), whereas it might have been expected to migrate in the opposite direction (toward the north). The simulated history obtained during this subperiod parallel the river's actual history in many respects. A contour map of the simulated channel depth was drawn at the end of fifth display interval (total intervals is 20) after 212 days after the start of the experiment. That date coincides with the beginning of the flood, and much of the river bed is submerged. By the end of the sixth display interval, the flood had largely subsided, although the water was still much higher than during the prolonged low-water stages that proceeded the flood (Fig. 13).

Comparison during the Second Sub-period

(Aug. 1967 – May 1968)

The second subperiod spans the period from August 27, 1967 through May 1, 1968 in terms of the record provided by aerial photographs, and display intervals 7 through 12, corresponding to day 255 through day 509 in terms of the record provided by the simulations. During this time, there were several floods of moderate size with maximum discharge rates of about $329 \text{ m}^3/\text{sec}$. Changes in the river channel during this subperiod were moderate, consisting mostly of accentuation of the channel forms established dur-

ing the flood in the first subperiod spans. It is useful to compare the two sets of aerial photographs to see the changes in channel form, showing mainly deposition in channel. Comparison of the contour map of the channel depth produced in the simulation with the aerial photographs for May 1, 1968 reveals a substantial degree of concordance. For example, the channel feature marked with an "X" is common to both the actual and simulated channels. Close comparison reveals other places at which the degree of concordance between actual and simulated channel features is relatively high.

Comparison during the Third Sub-period

(May 1968 – March 1969)

The second major flood in experiment duration existed with a peak discharge rate of about $850 \text{ m}^3/\text{sec}$ on May 28, 1968. This date coincided at the end of 13 display intervals, which showed the river to cover whole flood plain by water as first flood happened. This second major flood created substantial changes in the details of the channel, showing the meandering along the deepest part of river, and they persisted until at least 1969. Comparison of the aerial photographs taken on March 25, 1969 and the depth map obtained at the end of display interval 20 (Fig. 15) reveal a substantial degree of concordance between actual and simulated channels. For example, both actual and simulated channels migrated such that on edge of the channel was very close to the south bank. Furthermore, if it compared along deepest line of river, the form of meander from experiment is very similar to aerial photograph. Those successful results could

Fig. 14. Comparison between the result of experiment and aerial photograph at 1968. The channel shows to a more natural path as it was. "X" represents the same location between the photograph and the result of experiment.

Fig. 15. Comparison between the result of experiment and aerial photograph at 1969. The channel returned to a more meandering path with deposition and erosion. The arrow represented the location where the channel migrated toward inner side of channel curvature.

Fig. 16. Three cross sections of river basin with age boundaries were drawn at upper, middle, and lower parts in research area

mention not only the proof that the three-dimensional simulation based on theoretical approach was accurate but also the prediction that the changes of river channel and the depositional accumulation in flood plain occurred. Since the other advantage of this modelling was to represent the three-dimensional data of flood plain, three profiles of river basin was drawn with age boundaries at upper, middle, and lower parts in study area (Fig. 16). These profiles showed how to change the river bed from 1967 through 1969. It could mention the change of flood plain was due to depositional rather than erosional processes.

Conclusion

The most important conclusion in this study is that the results of experiments are very similar to the change of actual river. Simulation model presents the Arkansas river changes that affected a straight channel that was excavated within the river by the U.S. Army Corps of Engineers. Therefore, this study leads to approximate the river's actual behaviour to a reasonable degree, to predict the changes in river, and to help validate the simulation procedure's general applicability for experiments involving flow and sediment transport by rivers. Input data for simulation are topographic information after channelization, the composition and amounts of sediment filled in flood plain, daily river discharge rates for experimental span,

and *etc.* To obtain the initial flow velocities on daily base, the empirical relationship is obtained by analyzing statistically measurements of river depth and river discharge rates. The distribution data of sediments in three dimensions are obtained from geological logs and sieve analysis. Another empirical relationship is obtained between the river discharge rate and sediment load from observational data. The results of experiments represent flow velocities, distribution of sediment in flood plain, changes of shapes of river through time. The experiments compare favourably with field data, recreating similar patterns of fluid flow and sedimentation. The results of the experiments reconstructed with filling water in channel compare with aerial photographs showed changes during and following the dredging channel. The comparisons are based solely on the concordance between aerial photographs and contour maps of water depths obtained in the simulations.

The second key conclusion is that the two major floods, the one from June 20 to August 17, 1967 and the other from May 26 to June 2, 1968, brought about most of the changes in the channels in the overall period. The first flood destroyed the smoothly curving channel created by the Corps of Engineers. The development of meanders was slowly back to the original channel forms, with mainly depositional processes and minor erosional processes. The second major flood created substantial changes in the details of the channel, showing the meandering along the deepest part of river and persisting until the end of experiment. Comparison of the aerial photograph and the depth map from experiment reveals a substantial degree of concordance between actual and simulated channels, especially along thalweg (the locus of maximum depth in channel). Furthermore, the experiment showed the channel depositing a point bar but quickly reversed its direction so that the point bar was eroded. It is possible that the river dynamically re-established its former bed with depositional processes.

The results from experiments showed not only changes of channel but also composition and amount of sediments in flood plain. However, the distribution of sediment filled in flood plain could not compare due to lack of its actual data. However, it could infer that its distribution might be very similar to actual com-

position in study area, because the changes of channel shape was recreated by experiment and the topographic changes was calculated from the distribution of sediment and falling velocities of grain-sizes.

Therefore, the simulation model provide insight for understanding and spatial distribution of sediment bodies in fluvial deposits and the internal sedimentary structures of fluvial reservoirs. These theoretical approaches can be contributed to support the development of the new design criteria compatible with natural stream processes, especially drainage problem to minimize environmental disruption. It can be used to gain understanding about modern environments, and can also be used to recreate ancient environments whose histories are preserved in the stratigraphic record. Its potential applications lie in marine environment (nearshore process), where the coast is modified by erosion, transport and deposition of the geologic materials. Another applications are in groundwater and regional oil and gas exploration, as well as in exploitation drilling, where improved understanding and characterization of heterogeneities in oil and gas reservoirs and aquifers are important.

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要 旨

河川環境の三次元シミュレーション

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本研究はアメリカのオクラホマ州タルサ市周辺を流れ、流路が直線的なアーカンソー川を対象とし、それが自然に変遷する過程を数値シミュレーションによって再現した。シミュレーションに用いたデータは河川流域内の堆積物の分布、チャンネル化前後の地形、および流量などである。このため河川の流速、運搬される堆積物の分布、および組成などを毎日測定した資料から実験式を誘導している。シミュレーションの結果と空中写真とを比較した結果、河川の流れ、堆積物の分布、地形の変遷などによって形成された蛇行パターンと類似したものが再現できることがわかった。したがって、本研究は地質学的理解を高めるのみならず、河川流域の開発と洪水による浸蝕、堆積などの予測に役立つ。

キーワード：アーカンソー川、流路の変遷、三次元シミュレーション、浸蝕・堆積の予測

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