THE ALBERT SHIELDS STORY

By John F. Kennedy,[1] Member, ASCE

ABSTRACT: In the vast literature on sediment transport, rivers, and related topics, few if any names are more frequently cited than Albert F. Shields (1908–1974). Yet all of these citations are to a single publication: his doctoral thesis submitted to the Technischen Hochschule Berlin in 1936 in which he developed his ideas on *Aenlichkeitsmechanik* (similarity mechanics) for application to riverine sediment transport, ripple formation, and initiation of motion. Shields' most famous results are his graph for critical tractive force (initiation of particle motion), and secondarily, his sediment-transport formula. Presented here is the story of the many difficulties Shields encountered in conducting his research in Nazi Germany; his inability to find employment in hydraulics following his return to his native United States; the chance encounter with and promulgation of his work by Rouse; and his eventual relinquishment of hydraulics for a long and successful career in machine design.

INTRODUCTION

It is no doubt accurate to state that, in the vast and still burgeoning literature on river hydraulics, sediment transport, and related fields, one of the two or three most frequently cited names is that of Shields (1908–1974; Fig. 1). Yet all of these citations are to a single publication, "Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geshiebebewegung" ("Application of similarity principles and turbulence research to bed-load movement") [Shields (1936a, b); Fig. 2]. Although Shields had a long and productive engineering career, which continued until his retirement the year before his death, he published only one other fluids paper, and that was on seepage through dams (Weinig and Shields 1936). In fact, it was not until a few years before his death that he learned that his name and work had become famous in engineering hydraulics.

This is the story of Shields' sediment research, and of his abdication of hydraulics for machine design.

SHIELDS' HYDRAULICS INTERLUDE

Albert Frank Shields was born in Cleveland, Ohio, on June 26, 1908, the son of Frank Shields, a machinist. Following graduation from high school, he worked for 1 year to earn money to support his further education. In 1927 he enrolled at Cornell University and remained there for two semesters before transferring to Stevens Institute of Technology, where he obtained his bachelor's and master's degrees, both in mechanical engineering, in 1931 and 1933, respectively. In 1933 he was named a *Stipendiat* (fellowship recipient) of the Deutschen Akademischen Austauschdienstes E.V. (German Academic Exchange Service) of the Technischen Hochschule Berlin (TH Berlin). His plans included pursuit of research at the Preussischen Veruschsanstalt für Wasserbau und Schiffhau (Prussian Research Institute for Hydraulic Engineering and Shipbuilding; herein, PRI) that would serve as the basis for his dissertation, which would be submitted to TH Berlin for the degree *Doktor-Ingenieurs* (Doctor of Engineering).

In 1933 the world economy was wracked by the Great Depression. Shields had no personal resources, nor was his family in a position to assist him financially. Moreover, his stipend did not provide funds for any travel expenses. After pursuing several other possibilities, he finally gained passage to Germany by working on a freighter.

His intention was to do his doctoral-thesis research on ship-hull resistance, airfoil design, or some similar fluid-engineering topic that lent itself to an analytical approach. PRI was a logical choice for pursuit of his thesis research, for several reasons. First, Germany of the 1930s was at the forefront of fluids research and engineering, and PRI was one of its leading institutions in the field. It had become well known in the United States for its work, and through the fairly large number of Americans who had gone there to visit or conduct research. A particularly close tie was maintained with the U.S. Army Corps of Engineers' Waterways Experiment Station through assignments and visits of Corps officers to PRI. Several of these, notably Freeman Scholars, had obtained doctorates from TH Berlin and other educational institutions. Finally, it should be recalled that Berlin of the mid-'30s was perhaps the world's most vibrant city, and one of Europe's leading intellectual, cultural, and business centers. All of these features must have made Berlin a very attractive prospect to a young man from the Midwest United States.

Shields arrived in Berlin in November 1933, and after getting settled went to PRI to make arrangements for his research program on one of the aforementioned topics. When he met with the PRI director, Professor R. Seifert, he was informed that there were several openings in PRI projects on ship hydrodynamics, lifting-surface theory and experiment, and related topics of interest to Shields. However, to participate in one of these he would be required to reimburse PRI for a portion of the cost of the experiments each of the projects involved, which would amount to about 100 marks. Shields'

FIG. 1. Albert F. Shields (ca. 1946)

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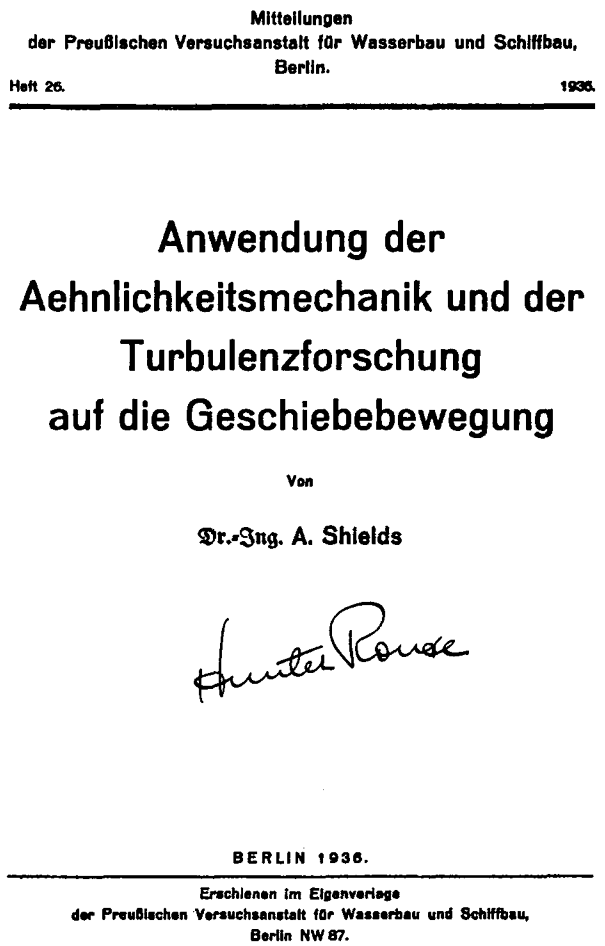

Mitteilungen
der Preußischen Versuchsanstalt für Wasserbau und Schiffbau,
Berlin.
Heft 26. 1936.

Anwendung der
Aehnlichkeitsmechanik und der
Turbulenzforschung
auf die Geschiebebewegung

Von

Dr.-Ing. A. Shields

Hunter Rouse

BERLIN 1936.

Erschienen im Eigenverlage
der Preußischen Versuchsanstalt für Wasserbau und Schiffbau,
Berlin NW 87.

FIG. 2. Cover of Rouse's Copy of Report Authored by Shields Describing His Work at Preussischen Versuchsanstalt für Wasserbau und Schiffhau

stipend did not provide for such expenses. In fact, because of inflation, the fixed sum he received soon became inadequate for him even to live on, his meager student lifestyle notwithstanding, and he shortly found himself doing considerable translation work just to meet living and incidental expenses.

The correspondence, if any, between Shields and PRI prior to his arrival in Berlin apparently has been destroyed. It is reasonable to assume that he did not make prior arrangements for his research at PRI, and that some misunderstanding must have arisen concerning his areas of research interest, and his ability to cover any costs it involved.

In any event, it was made clear in his discussions with PRI Director Ludin that the only available research assignment that would not entail some expenses that Shields would have to bear was concerned with sediment transport by river flows, and in particular *Geshiebebewegung* (bed-load transport). This project was one phase of a continuing basic investigation of sediment transport by water, and of scaling laws for movable-bed models. The investigation had been initiated by Franz Eisner, who had committed suicide as a result of Nazi harassment about a year prior to Shields' arrival in Berlin. The next phase of this investigation, which was offered to Shields as a dissertation topic, was to study the effects of particle specific gravity on bed-load discharge, bed forms, initiation of motion, etc. Two earlier phases of the PRI bed-load investigation had been conducted by two other Americans, both of them Freeman Scholars and career Army Corps of Engineers officers. The first of these was Hans Kramer (1894–1957), who was born in Magdeburg, Germany; immigrated with his parents to the United States in 1902; attended the University of Michigan; graduated from the U.S. Military Academy at West Point in 1918; received a master's degree from the University of Pennsylvania in 1928; remained on active duty in the Army until 1945, when he retired with the rank of Brigadier General; and thereafter practiced engineering as a consultant. His tenure as an ASCE Freeman Scholar began in September 1930, and was extended for a second year to enable him to complete research at PRI for his *Doktor-Ingenieurs* dissertation, "Modellgeshiebe und Schleppkraft" ("Bed load and bed shear") (Kramer 1932, 1935), which was submitted to the Technical University of Dresden in 1932. His dissertation was dedicated to "Geheimen Rat Dr.-Ing. Dr. Hubert Engels, the father of river research." Kramer's dissertation was concerned primarily with the determination of model bed-material gradation curves that would dynamically reproduce at small scale the bed-load transport characteristics of prototype rivers over wide ranges of discharge (from below the limit for initiation of motion, to values at which the entire bed surface is mobilized); and with computation of critical tractive force.

The second American, also an Army officer and Freeman Scholar, to carry out a study in the PRI series of sediment investigations was Hugh J. Casey (1898–1981). He had commenced his engineering studies at Brooklyn Polytechnic Institute; transferred to West Point, where he graduated in 1918; played central roles in the planning and construction of several major Corps of Engineers projects in the United States, including the Pentagon; spent much of his military career in the Far East, particularly the Philippines, where he served as General MacArthur's chief engineer (he accompanied MacArthur during World War II, from his flight from Corregidor, to the Japanese surrender at Tokyo); advanced to the rank of Major General before retiring from the Army in 1949; and then held a series of high-level consulting and administrative posts in government and business (including vice president of Schenley Industries, and chairman of the New York Transit Authority). He was awarded a Freeman's Scholarship by the American Society of Mechanical Engineers (ASME) in 1933, and arranged to stay in Berlin for a second year to complete his dissertation research, which was submitted to TH Berlin. His PRI publication, "Uber Geschiebebewegung" ("On bed-load movement") (Casey 1935) reports an extensive set of flume experiments utilizing seven different quartz sands and three sand mixtures for bed material. The study was concerned principally with the effects of particle size and size range on bed-load discharge, bed forms, bed roughness, and so forth.

The project offered to Shields was a continuation of those conducted by Kramer and Casey, and was to be concerned with the effects of particle specific gravity on bed-load transport rate, initiation of motion, bed forms, and so forth. Shields had no interest in, nor even any prior knowledge of, sediment transport or river hydraulics, but accepted the project as a last resort. PRI's contribution to the investigation included the laboratory equipment and supplies, two workmen to assist in conduction of the experiments, and use of an attractive, private office. The office turned out to be the one in which Eisner had committed suicide. This was itself depressing, and Shields' depression was compounded when he learned that Eisner had been the only PRI staff member who had known anything about the *Geschiebebewegung* project circumstance was forcing him to undertake, and for that matter the only PRI staff member who had any interest in, or knowledge about, sediment transport and river hydraulics. Thereupon, Shields proceeded to read the literature on the subject, but found it to be disorganized and fragmented, and its research problems not amenable to analytical treatment. Still another blow to

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his morale came when he went to the TH Berlin to meet his *Referent* (thesis advisor), Dr. Ing. Dr. techn. h.c., Adolf Ludin, who turned out to be an ardent Nazi with an intense dislike for foreigners in general and Americans in particular. This, however, proved to be not too great a distraction, because Shields was to see him only twice. At their first meeting, Ludin severely reprimanded Shields for having not come to see him to discuss his research project before it was under way at PRI. Ludin was also angry because Shields was pursuing the research at PRI instead of in the TH Berlin laboratory, which Shields didn't even know existed and which he could not have used anyhow because it was not equipped for the experiments, and the researcher had to bear equipment and related expenses. Finally, Ludin wasn't interested in the topic of Shields' thesis, primarily it appears because it was not of the professor's choosing. Their second meeting was when he stood for oral examination of his thesis. (Ludin also served as Casey's thesis *Referent*. In the acknowledgments of his dissertation, Casey expresses special thanks to Ludin "who, despite a severe illness, was always prepared to provide valuable advice to further the investigation" [Casey (1935) page 70]. Apparently Ludin was mellowed by his illness (a painful facial neuralgia) and hardened by his conversion to Nazism).

By April 1934 Shields' laboratory studies were under way. For his experiments with coal and three of the coarser barite materials, he used the 80.7-cm-wide, 14-m-long flume that Kramer (1932, 1935) employed. Experiments with amber, granite fragments, and the finer barite sediment were conducted in Casey's (1935) 40-cm-wide, 14-m-long flume. It appears that Shields utilized essentially the same experimental procedure as his two compatriot predecessors. The two assistants assigned to him were capable and diligent, and the laboratory work proceeded apace while leaving him ample time for analysis and interpretation of the emerging data, and to do translation work to supplement his stipend.

At about the time he was midway through his experimental work, Shields was informed that his master's degree from Stevens Institute of Technology had not been accepted by the Prussia Ministry of Education as equivalent to a German *Diplom Ingenieur* degree, and he therefore was not eligible to pursue his doctoral research. (Hunter Rouse had found himself in a roughly similar situation in 1927 at TH Karlsruhe. Upon being informed by the Baden Ministry of Education that his bachelor's degree from Massachusetts Institute of Technology was inadequate preparation for pursuit of his doctoral research, Rouse, too, proceeded to work toward his *Diplom*. However, he found the courses and assignments a needless repetition of his MIT undergraduate work. Upon petition, the Baden Ministry of Education permitted him to continue his doctoral research under the condition that he would return to MIT and obtain a master's degree before being examined for his *Doktor-Ingenieurs*.) The PRI director, Professor Seifert, reluctantly allowed Shields to discontinue his research in order to work toward his *Diplom*.

His *Diplom Arbeit* (undergraduate project) was done under Professor H. Föttinger (1877–1945) at TH Charlottenburg. Föttinger was a leading authority on hydraulic machinery who, although he did extensive research on pumps, turbines, and cavitation, is perhaps best known for his work on fluid torque converters. He held more than 100 patents for his inventions. Föttinger assigned Shields to work directly under Dr. Weinig, a *Privat Dozent* (private university lecturer) who was a gifted applied mathematician with a particular flair for conformal transformation. Shields' *Diplom Arbeit* (Weinig and Shields 1936) involved hodgraph mappings of free-surface seepage flows through dams, and then mapping conformally transforming the hodgraph-plain flows into geometric configurations for which the complex velocity potentials could be easily derived. This was truly a primary effort. According to Bear (1972), Hamel (1934) developed the hodgraph method for study of forced-media flow, and Dachler (1936) introduced its application in applied ground-water hydraulics. Thus it is reasonable to infer that Weinig and Shields were doing their applied ground-water analysis concurrently with, and independent of that of his *Diplom Arbeit* concurrently with Dachler, whose work published in 1934 (Hamel 1934) and 1935 (Hamal and Günther 1935) is sited by Weinig and Shields (1936). This contribution alone would have been enough to earn Shields' name a permanent place in the literature on ground-water hydraulics, but it has been almost completely overlooked, at least in the English-language literature on the subject. The work was praised by Föttinger, who gave it the grade "sehr gut Bestanden." Shields received a very welcome DM75 for publication of this work in the German journal *Wasserkraft und Wasserwirtschaft* (Weinig and Shields 1936).

Meanwhile, Shields' scholarship, which had been renewed for a second school year, ran out in the spring of 1935. Consequently, his most pressing challenge upon completion for his *Diplom Arbeit* was to find another source of income to live on. He could find no work in the Berlin area, nor elsewhere in Germany, and eventually took a steel-mill job during the summer of 1935 in what was then the Saar region of France. Shields' extension of his leave of absence from PRI beyond the time required to complete the *Diplom Arbeit*, and his leaving Germany without obtaining Professor Seifert's permission or even informing him, so enraged Seifert that he forbade him access to PRI. Shields was very disappointed and distressed at this turn of events, because he had invested so much time and effort in the sediment research and would not be permitted to use even the results he already had obtained. After considerable agonizing he decided to start doctoral research in another field, likely in the United States. While making his farewell visits to friends from PRI, two of them pointed out that Seifert really needed Shields to bring the project to an orderly completion, and opined that he had only wanted to teach Shields a lesson about respecting authority and keeping his superiors informed. Shields arranged an appointment to meet Seifert, made a suitably contrite apology to him, and in the fall of 1935 recommenced his work on the *Geshiebebewegung* project, which then proceeded without further interruption and was completed within a few months.

The experiments were completed in spring 1936, and the PRI project report (Shields 1936a) and Shields' dissertation (1936b) were finished shortly thereafter. The two publications are identical. Professor Seifert passed Shields' manuscript on to Dr. Kopp, who had been recently hired by PRI, and asked him to review and edit it. Dr. Kopp's principal suggestion was that a paragraph be added at the end of each of the three sections of the manuscript to summarize the important results of the section and their importance and practical application.

He submitted his dissertation to TH Berlin on May 20, 1936, and it was examined on June 30, 1936. His *Doktor-Vater*, Professor Ludin, listened in stony silence to Shields' oral presentation, never raising a question nor offering any comment. After Shields had finished his oral presentation, Professor Ludin proceeded to read the concluding paragraph of each section, visibly sneered, and made some remarks to the effect that he didn't care so much what the results or their significance were as long as Shields didn't take credit for experiments he had not made [in his thesis, Shields utilized flume data of Kramer (1932), Casey (1935), Gilbert (1914), and the Army Waterways Experiment Station]. Thereupon Shields and Ludin parted as they had met—with minimum cordiality. Shields didn't even have his own copy of this thesis; it had been borrowed by one of the examiners. It was not until several days later that he was informed that his disser-

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tation was accepted with the grade *gut Bestanden* (a grade of approximately C). Shields was disappointed by the low grade, and more anxious than ever to go home. However, he still had an obligation to PRI which required him to continue working there several more months.

While conducting his flume runs, Shields had made some flow-visualization experiments by introducing dye into the water. He had noted the differences in intensity and time and length scales between the free-stream and the boundary-layer turbulence. To occupy the time before his return to the United States, he undertook some analysis and experiments to relate the equilibrium conditions between bed load and suspended load on the basis of these differences. He had just started this work when Dr. Georg Weinblum of PRI offered him the opportunity to make theoretical wave-resistance calculations for a series of ship hulls that were to be tested at PRI. Shields jumped at the opportunity to do analytical work, of the type he had sought originally, under the direction of the famous Dr. Weinblum. All further work on sediment was dropped at this point.

In the course of his work at PRI, Shields had become a friend of several Corps of Engineers officers who were visiting or on assignment to the institute. One of them, a Lieutenant Nichols, thought so highly of Shields' research and other talents that he offered him a position at the Army Waterways Experiment Station in Vicksburg, Miss. Shields planned to visit the Station to discuss employment following his return to the United States, in late 1936. However, his family, who hadn't seen him for over three years, wouldn't hear of him being away any longer, so he sought work first in Cleveland, then New York. He did not succeed in finding full-time employment, so he undertook design jobs on a freelance basis for various manufacturing enterprises. Most of the designs were for machine tools, paper-converting equipment, and machines for making packaging. Some patents were applied for and received, and after a couple of years he found that his design services were being actively sought.

During the summer of 1937, while still seeking full-time employment, he made a trip to California, and while there visited and applied for a position at Caltech. He had learned from Georg Weinblum of the fluids research being done there by von Kármán, Clark Millikan, and others. He met Millikan and showed him the potential-flow calculation he had done for Föttinger in Berlin. He was told that there were no openings at Caltech at the time, whereupon he returned to New York. This was to be the only fluids research and engineering job he applied for.

In late 1937 he finally obtained a full-time job, with the S&S Corrugated Paper Machinery Co., Inc., of Brooklyn, N.Y., as a machine designer. He remained with this company in a series of progressively more responsible jobs, eventually becoming vice president for engineering, until his retirement from the firm in January 1973. At S&S, he was affectionately known as "Doc," and provided the leadership for its engineering department during most of his 37 years with the company. At the time of his retirement he held more than 200 patents in the corrugated-box machinery design field. By his own account, he lived very comfortably for over 30 years on his patent-royalty income. He resided in New York from the 1930s onward, and in his later years also had a summer home in Connecticut, and a winter home in Jamaica, Florida.

In 1972 Shields made two trips to Europe, one in the spring, and a second in the summer to give a talk before an industry group in Berlin. He did not feel well during the second one, and following the return to his Connecticut home suffered an apparent heart attack on the golf course and was taken to Danbury Hospital in a coma. There it was found that he had cancer in his left lung, which was removed. After nearly 2 years of treatment with chemotherapy in New York and acupuncture in South Carolina and Florida, he succumbed on July 23, 1974. He was survived by his widow, Anne; three sons; two daughters; and six grandchildren.

SHIELDS AND ROUSE

Shields' life, and especially his career, might have turned out quite differently if, during his 1937 stop at Caltech, he had visited a different group. He apparently was unaware that one of the world's then most active and productive sediment-research programs was being conducted by several of the future giants of hydraulics in another Caltech building that stood no more than 100 m from the Guggenheim Laboratory, where he met with Clark Millikan. Included in that group were Robert T. Knapp, Vito Vanoni, Arthur T. Ippen, Hunter Rouse, and, a few years later, H. A. Einstein. They and several other Caltech and government engineers were engaged in an extensive sediment-research program sponsored by the U.S. Department of Agriculture Soil Conservation Service (SCS). Shields would have been a natural addition to this team.

During his student days in Germany, Rouse had spent four weeks of the summer of 1930 at PRI studying under Eisner. In the course of a 1938 trip to visit in-laws and laboratories in Europe, Rouse returned to PRI. It was there that he learned about Shields' work and obtained a copy of his dissertation/report. En route back to Caltech, Rouse attended the famous Fifth International Congress for Applied Mechanics, in Cambridge, Mass., to present his paper on sediment suspension in a turbulence jar (Rouse 1938). Following his return to Caltech, he studied Shields' dissertation and was so impressed that he made arrangements for it to be translated into English by two of the SCS employees engaged in the Caltech sediment program, W. P. Ott and J. C. van Uchelen. Through the translation, Shields' work became known to the Caltech sediment-research group, and was used in publications, teaching, and other activities. Of particular importance to dissemination of Shields' critical-tractive, forced diagram was the use of it by Rouse in three or four of his papers during the next decade. By the 1940s, the Shields diagram and Shields transport formula were well entrenched in the English-language sediment-transport and river-mechanics literature of the day.

In 1939, while reviewing the material from the Fifth International Congress for Applied Mechanics, Rouse happened to notice Shields' name in the list of attendees that accompanied the group photograph. He obtained his address from the Congress secretary, and wrote Shields a very complimentary letter about his dissertation. Shields' opening paragraph of his response letter to Rouse is

> My heartiest thanks for the very kind letter you have written me! This has been an especially appreciated since it is not only the first nice thing I have heard about that work but is even the first comment that has been made on it to me.

In this initial letter to Shields, Rouse asked for a tabulation of the laboratory data, which were not included in Shields' dissertation/report. Shields responded that he did not have the data, because it had remained the property of PRI. For that matter, as he went on to point out, he had only recently obtained a copy of his own dissertation/report, by purchasing one from PRI. Professor Seifert had promised to send Shields two hundred copies of the report as soon as it was received from the printer, and later assured him that they had been sent. They were never received by Shields. In 1967 and 1968 Rouse again sought to obtain the Shields data. Meanwhile, PRI's building and records had been destroyed by World War

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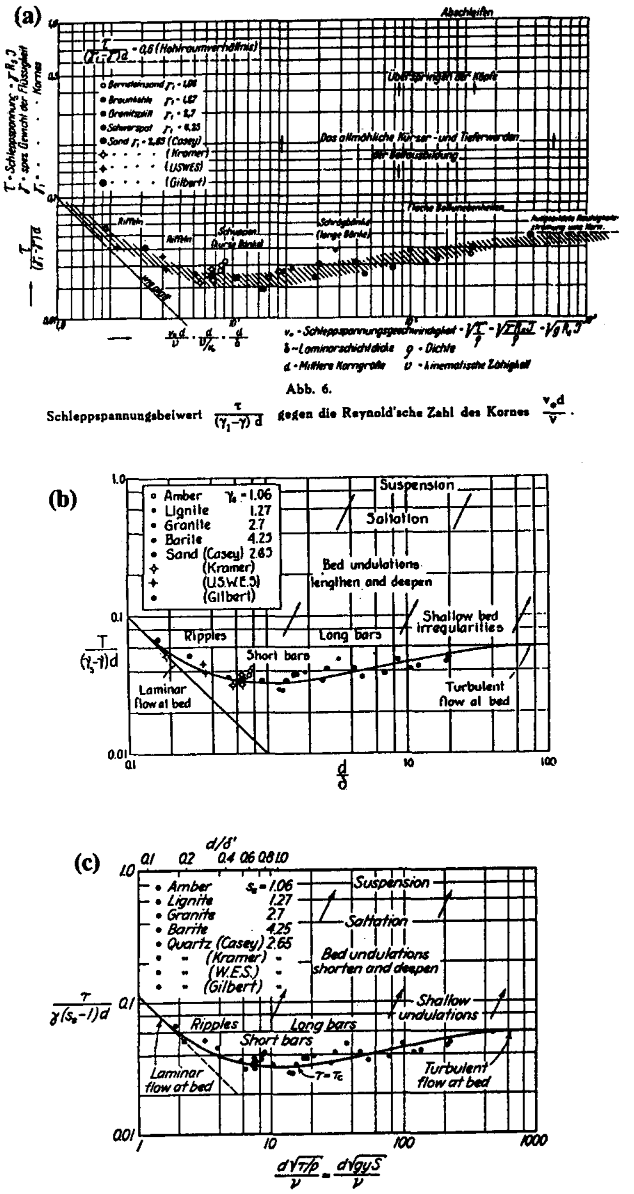

FIG. 3. Evolution of Shields' Diagram for Critical Tractive Force: (a) Shields' Original Diagram (Shields 1936a, b); (b) First Appearance of Shields' Diagram in English Literature (Rouse 1939); (c) Later Rendering of Shields' Diagram (Rouse 1950)

II bombing. Rouse's further inquiries to several other German laboratories, as well as those at Wallingford, U.K., and Vicksburg, proved fruitless. One must conclude that these data are permanently lost.

Another brief exchange of correspondence between Shields and Rouse occurred in 1973 and 1974, while Rouse was researching his *Hydraulics in the United States, 1776–1976* (Rouse 1976). By this time Shields knew that he was terminally ill, and his letters had a distinctly melancholy tone. Rouse sent him copies of *History of Hydraulics* (Rouse and Ince 1955), and the Caltech translation of his Berlin dissertation/report. Shields was surprised to learn how widely accepted and utilized his work had become, and clearly derived great satisfaction from this knowledge. Following his death, Mrs. Shields wrote Rouse that her husband had kept *History of Hydraulics* and the translation of his dissertation/report by his chair or bed for repeated occasional reading. He commented to her more than once how impressed he was by his own work after seeing it again for the first time in nearly 40 years, especially

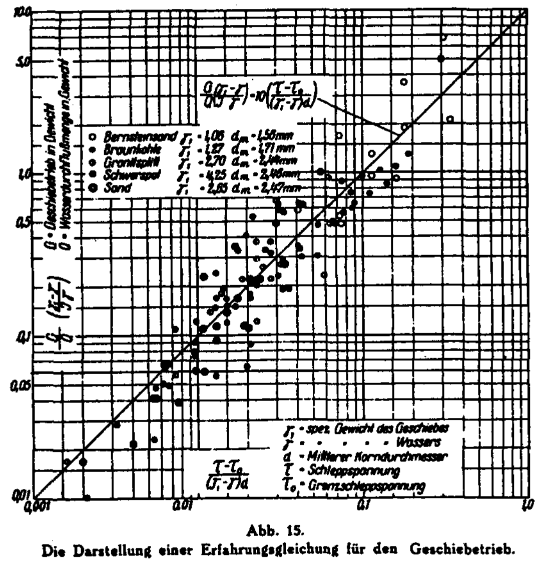

FIG. 4. Graph Presented by Shields to Validate His Bed-Load-Discharge Formula and Evaluate Its Constant

when he recalled the trying circumstances under which it was conducted.

Shields' best known results are his diagram for critical tractive force, shown in Fig. 3 in successive versions, as evolved principally by Rouse; and his bed-load-discharge formula

$$\frac{G}{Q}\frac{\gamma_1 - \gamma}{S\gamma} = 10\,\frac{\tau - \tau_o}{(\gamma_1 - \gamma)d} \tag{1}$$

where G = bed-load discharge; Q = fluid discharge; γ_1 = grain specific weight; s = energy-gradient slope; γ = fluid specific weight; τ = bed shear stress; τ_o = critical tractive force; and d = mean grain diameter. Fig. 4 is Shields' (1936 a, b) plot presented to validate (1) and to determine the coefficient.

Fig. 3(a) shows Shields' diagram as it appears in his dissertation/report, (e.g., Rouse 1950). Fig. 3(b) depicts the figure as it first appeared in the English-language literature, in a paper presented by Rouse (1939) at the January 1939 ASCE annual meeting. In his paper, Rouse presented, developed, and extended several of Shields' ideas. Contributions of particular note are Rouse's greater use and interpretation of the significance of the ratio of the viscous sublayer thickness, γ', to the particle diameter, d. This ratio appears as an auxiliary scale in Rouse's later versions of the diagram [Fig. 3(c)]. Shields' *Aenlichkeits* ideas enter through similarity of the mean-flow (logarithmic-form) velocity profiles from which the near-bed velocity that initiates particle motion is selected.

The two nondimensional groupings of variables appearing in the diagram presented by Shields were obtained by equating the shear (friction) resistance of the top layer of bed grains to the fluid drag exerted on the bed; and relating the fluid drag expressed in terms of a near-bed local velocity to $v_* d/\nu$ (where v_* = shear velocity; and ν = kinematic viscosity) which appears in the Kármán-Prandtl velocity-distribution relations. Of particular note is Rouse's replacement of a shaded zone of critical tractive force by a single line. Shields presented only an outline description of his apparatus and procedure, and referred readers to Kramer (1932) and Casey (1935) for further details, which implies that he followed the same procedures. Kramer (1932) did not attempt to define or identify an incipient motion condition for each of his series of constant-slope experiments. Instead, in his discussion and data tabulation he identifies for each set of constant-slope experiments the upper limit and lower limit of conditions

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within which initiation of motion could be said to occur. The depths and bed shear stresses for these vary in Kramer's data by a factor of about 1.5 to 2.2. It is reasonable to assume that Shields also followed this procedure, and he did utilize Kramer's data. However, Shields' shaded region does not cover such a wide range of critical shear stress, nor does the number of points for each material correspond to the number of sets of experiments reported for that material. Kramer made runs at four different slopes for each of his three sands; but Shields shows three points, not twelve, for Kramer's data. Thus it appears that Shields did some sort of averaging to obtain a single critical-condition point for each sediment, and thereby reduced the range of bed stress corresponding to critical conditions. He does state, however, that "the points for a bed load of uniform grain size and angular shape yield a single curve" [Shields (1936a) page 12]. It remained for Rouse to draw the curve.

CONCLUSION

Shields (and his predecessors whose data he used) were canny in the way they conducted their experiments. In laboratory-flume experiments, one is severely limited in the ranges of flow depth, velocity, and particle size that can be covered. However, submerged specific weight can be varied widely if the particle specific gravity is close to unity. In the case of Shields' diagram, the particle specific gravity varies from 10.6 to 4.25, so the submerged specific gravity ranges from 0.06 to 3.25, a factor exceeding 50. Thus by varying particle density, Shields was able to cover a much wider range of critical tractive force, from that induced purely by viscous forces to turbulence driven particle motion, then would have been the case had he elected, say, particle size or flume slope as a dependent variable. This enabled him to cover the entire range of interest for critical tractive force.

An oft-told story about Shields' diagram relates that the points were obtained by extrapolating to zero the bed-load-discharge data, plotted in the format of his transport relation, (1). Although it is not entirely clear how the Shields' diagram points were obtained, there is nothing in his dissertation/report to suggest that it was in this way.

Shields' bed-load-discharge formula, (1) and Fig. 4, is of the same general form as the DuBoys formula. He arrived at the form of the relation utilizing *Aehnlichkeitsmechanik* (similarity mechanics, or similarity principles) with a heavy infusion of dimensional analysis. Shields cautioned that the formula "has not been written to depict a universal formula for bed-load movement (without ripple formation), from which numerical values may be safely deduced. It is rather an abbreviated form to express the influence of the various factors upon bed-load movement" [Shields (1936a) page 20]. He then went on to examine each of these factors. He also recognized that true dynamic similarity of sediment discharges of model and prototype flows can exist only if the bed forms are also similar. Therefore, he limited his derivation, as follows: "For this reason, we begin by excluding from our considerations bed-load movement in the form of ripples, since this is a special form of movement, which has but little practical significance in comparison with natural processes. Thus, an attempt is made to establish a formula for much smaller *H*/*L* values [height: length of bed formation] such as occur shortly after the beginning of movement" [Shields (1936a) page 20]. In practice, the limitations he placed on (1) have been largely ignored and the formula used to compute bed-load discharge over the full range of transport conditions, and to compute even the total-load discharge of flows with heavy suspended-load discharges.

His diagram for critical tractive force, and secondarily his transport equation, earned Shields' work a permanent place in the literature on river engineering and sediment transport. Of perhaps greater importance, and generally overlooked, is his pioneering use of *Aehnlichkeitsmechanik* to the analysis of flow problems that are otherwise largely intractable. As practiced by Shields, this involves analytical fluid and solid mechanics to the extent possible, supplemented with dimensional reasoning and analysis to arrive at the important nondimensional parameters. His central thesis is that these nondimensional quantities have equal values in dynamically similar sediment-transporting (and other) flows. His dimensionless shear stress, for example

$$\frac{\tau}{(\gamma_1 - \gamma)d} \tag{2}$$

which was arrived at in this way, has been derived in several different forms by a variety of means in the works of numerous subsequent investigators, and is one of the cornerstones of sediment-transport mechanics. Shields' *Aehnlichkeitsmechanik* has found wide application in sediment-transport analysis, from the early work of Einstein (1950), to Engelund (1966), to Karim (1981) and Brownlie (1983), to Lyn (1988). His introduction of it to river mechanics is perhaps his greatest contribution.

In his brief excursions into sediment research and groundwater analysis, and throughout his long career as a machine designer and inventor, Shields demonstrated that he was an extremely gifted, innovative, energetic engineer. What a pity for hydraulics that the hydraulicians of the 1930s found no place for him in their ranks!

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