Zbornik radova Prirodno-matematičkog fakulteta-Univerzitet u Novom Sadu
knjiga 14,1 (1984)
Review of Research Faculty of Science-University of Novi Sad, Volume 14,1 (1984)

ON COMMON FIXED POINTS IN METRIC AND PROBABILISTIC METRIC SPACES WITH CONVEX STRUCTURES

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ABSTRACT

In this paper we prove some generalizations of Theorems 1 and 2 from [5] in metric and probabilistic metric spaces with convex structures.

W. Takahashi introduced in [14] a notion of convexity in metric spaces and generalized some fixed point theorems in Banach spaces. Some fixed point theorems in metric spaces with convex structures are obtained by S. Itoh [8], S.A. Naimpally, K.L. Singh and J.H.M. Whitfield [10], [11], B.E. Rhoades, K.L. Singh and J.H.M. Whitfield [12] and L.A. Tallman [17] and for metric spaces of the hyperbolic type in [3].

In the first part of this paper we shall prove a generalization of Theorem 1 from [5] where the measure of noncompactness Ψ is, in this paper, the Kuratowski measure of noncompactness α. The second part of this paper contains a generalization of Theorem 2 from [5] on probabilistic metric spaces with a convex structure.

AMS Mathematics subject classification (1980): 47H10
Key words and phrases: Convex structures, common fixed points, metric and probabilistic metric spaces.

1. First, we shall give some definitions, where $I = [0,1]$.

DEFINITION 1. [16] *Let* X *be a metric space. A mapping* $W : X \times X \times I \to X$ *is said to be a convex structure if for every* $(x,y,\lambda) \in X \times X \times I$:

(1) $d(u,W(x,y,\lambda)) \leq \lambda d(u,x) + (1-\lambda)d(u,y)$, *for every* $u \in X$.

A metric space with a convex structure will be called a *convex metric space*. There are many convex metric spaces which cannot be imbedded in any Banach space [16].

REMARK. From (1) we obtain, for $\lambda = 1$ and $u = x$ that $d(u,W(x,y,1)) = 0$ which implies that $x = W(x,y,1)$. Similarly it follows that $y = W(x,y,0)$. The mapping W is not continuous in general, however if X is compact then W is continuous [16]. If a convex metric space X is such that $co_W(A)$ is compact for every finite subset A of X, where we denote by $co_W(M)$ $(M \subseteq X)$ the intersection of all convex sets N such that $M \subseteq N$ (A set $N \subseteq X$ is *convex* if for every $(x,y,\lambda) \in N \times N \times I : W(x,y,\lambda) \in N$) then the mapping W defines a pseudoconvex structure on X in the sense of the Definition in [7].

DEFINITION 2. *Let* X *be a convex metric space,* $x_o \in X$ *and* $S : X \to X$. *The mapping* S *is said to be* (W,x_o)-*-convex if for every* $z \in X$ *and* $\lambda \in I$:

$$W(Sz,x_o,\lambda) = S(W(z,x_o,\lambda)).$$

REMARK. If X is a Banach space and $W(x,y,\lambda) = \lambda x + (1-\lambda)y$, for every $(x,y,\lambda) \in X \times X \times I$, every homogeneous mapping $S : X \to X$ is $(W,0)$-convex.

DEFINITION 3. [12] *A convex metric space* X *satisfies condition* (II) *if for all* $(x,y,z,\lambda) \in X \times X \times X \times I$: $d(W(x,z,\lambda),W(y,z,\lambda)) \leq d(x,y)$.

The Kuratowski measure of noncompactness of a set

$D(D \subseteq X)$ is defined by $\alpha(D) = \inf\{\varepsilon | \varepsilon > 0$, there exists $\{A_j\}_{j\in J}$, J is finite, such that $D \subseteq \bigcup_{j\in J} A_j$ and $\operatorname{diam} A_j < \varepsilon$, for every $j \in J\}$.

A continuous mapping $T : X \to X$ is said to be α-densifying on $M \subseteq X$ if for any bounded subset D of M, the set $T(D)$ is bounded and:

$$\alpha(D) > 0 \Rightarrow \alpha(T(D)) < \alpha(D).$$

In [2], the following theorem is proved.

THEOREM A. *Let* S *and* T *be continuous mappings of a complete metric space* (X,d) *into itself. Then* S *and* T *have a common fixed point in* X *if and only if there exists a continuous mapping* $A : X \to SX \cap TX$, *which commutes with* S *and* T *and satisfies the inequality:*

$$d(Ax,Ay) \leq qd(Sx,Ty), \text{ for every } x,y \in X,$$

where $q \in [0,1)$ *and* S,T *and* A *then have a unique common fixed point.*

We shall use Theorem 1 in the proof of the following theorem.

THEOREM 1. *Let* (X,d) *be a complete, convex metric space which satisfies condition* (II), A,S *and* T *continuous mappings from* X *into* X *such that* A *commutes with* S *and* T, $AX \subseteq SX \cap TX$, AX *be bounded and the following conditions are satisfied:*

1. *For every* $x,y \in X$:

$$d(Ax,Ay) \leq d(Sx,Ty).$$

2. *There exists* $m \in \mathbb{N}$ *such that* A^m *is* α-*densifying on* $\{W(z,x_o,\lambda) | z \in AX, \lambda \in [0,1]\}$ *for some* $x_o \in X$.

If S *and* T *are* (W,x_o)-*convex there exists* $x \in X$ *such that* $x = Ax = Sx = Tx$.

P r o o f: Let $\{k_n\}_{n\in\mathbb{N}}$ be a sequence of real numbers from $(0,1)$ such that $\lim_{n\to\infty} k_n = 1$ and for every $n \in \mathbb{N}$:

$$A_n x = W(Ax, x_o, k_n), \text{ for every } x \in X.$$

We shall prove that for every $n \in \mathbb{N}$ there exists $x_n \in X$ so that

$$x_n = A_n x_n = Sx_n = Tx_n .$$

Since X satisfies condition (II) we have that:

$$d(A_n x, A_n y) = d(W(Ax, x_o, k_n), W(Ay, x_o, k_n)) \leq k_n d(Ax, Ay) \leq$$

$$\leq k_n d(Sx, Ty)$$

for every $x,y \in X$. Further, from $AX \subseteq SX \cap TX$, since S and T are (W,x_o)-convex, it follows that:
$A_n x = W(Ax, x_o, k_n) = W(Sz_x, x_o, k_n) = W(Tw_x, x_o, k_n)$ and so
$W(Ax, x_o, k_n) = S(W(z_x, x_o, k_n)) = T(W(w_x, x_o, k_n)) \in SX \cap TX$. Thus $A_n X \subseteq SX \cap TX$ and since A and S are commutative we have:
$A_n Sx = W(ASx, x_o, k_n) = W(SAx, x_o, k_n) = S(W(Ax, x_o, k_n)) = SA_n x$, for every $x \in X$ and every $n \in \mathbb{N}$ and similarly $A_n Tx = TA_n x$, for every $n \in \mathbb{N}$ and every $x \in X$. Thus, all the conditions of Theorem A are satisfied and there exists $x_n \in X$ such that $x_n = A_n x_n = Sx_n = Tx_n$. Furthermore:

$$d(x_n, Ax_n) = d(A_n x_n, Ax_n) = d(W(Ax_n, x_o, k_n), Ax_n) \leq$$

$$\leq k_n d(Ax_n, Ax_n) + (1-k_n) d(Ax_n, x_o)$$

and since AX is bounded, it follows that:

(2) $$\lim_{n\to\infty} d(x_n, Ax_n) = 0.$$

Let us prove that (2) implies:

(3) $$\lim_{n\to\infty} d(x_n, A^m x_n) = 0.$$

Since for every $k \in \mathbb{N}$:

$$d(A^k x_n, A^{k+1}x_n) \leq d(S(A^{k-1}x_n), T(A^k x_n)) = d(A^{k-1}Sx_n, A^k Tx_n) =$$

$$= d(A^{k-1}x_n, A^k x_n)$$

it follows that:

$d(A^k x_n, A^{k+1}x_n) \leq d(x_n, Ax_n)$, for every $k \in \mathbb{N}$ and every $n \in \mathbb{N}$ and so:

$$d(x_n, A^m x_n) \leq \sum_{k=0}^{m-1} d(A^k x_n, A^{k+1}x_n) \leq md(x_n, Ax_n).$$

This implies that (3) is satisfied. Let us prove that the set $\{W(Ax, x_o, \lambda) | x \in X, \lambda \in (0,1)\}$ is bounded. This follows from the inequality:

$$d(u, W(Az, x_o, \lambda)) \leq \lambda d(u, Az) + (1-\lambda) d(u, x_o) \text{ for every } (z,u) \in X \times X$$

since AX is bounded. From the relations $x_n = A_n x_n$ $(n \in \mathbb{N})$ we obtain that $\{x_n | n \in \mathbb{N}\} \subseteq \{W(Ax, x_o, \lambda) | x \in X, \lambda \in (0,1)\}$ and so the set $\{x_n | n \in \mathbb{N}\}$ is bounded. Furthermore, for every $\varepsilon > 0$ we have from (3) that:

$\alpha[\{x_n | n \in \mathbb{N}\}] \leq \alpha[B(A^m(\{x_n | n \in \mathbb{N}\}), \varepsilon)] \leq \alpha[A^m(\{x_n | n \in \mathbb{N}\})] + 2\varepsilon$ ([10]) where $B(A,\varepsilon) = \{x \in X | d(x,A) < \varepsilon\}$ $(A \subseteq X)$ and so:

$$\alpha[\{x_n | n \in \mathbb{N}\}] \leq \alpha[A^m(\{x_n | n \in \mathbb{N}\})] .$$

This implies that $\alpha[\{x_n | n \in \mathbb{N}\}] = 0$ and there exists a convergent subsequence $\{x_{n_k}\}_{k \in \mathbb{N}}$. Let $\lim_{k \to \infty} x_{n_k} = y$. Then from:

$$d(y, Ay) \leq d(y, x_{n_k}) + d(x_{n_k}, Ax_{n_k}) + d(Ax_{n_k}, Ay)$$

and (2), since A is continuous, it follows that $y = Ay$. From $x_{n_k} = Sx_{n_k} = Tx_{n_k}$, $k \in \mathbb{N}$, since S and T are continuous, we obtain that $y = Ay = Sy = Ty$.

2. If there exists $m \in \mathbb{N}$ such that $\overline{A^m X}$ is compact, we can prove a generalization of Theorem 2 from [5] for probabilistic metric spaces with a convex structure.

A triplet $(S,\mathcal{F},t)$ is a *Menger space* [14] if and only if S is an arbitrary set, $\mathcal{F} : S \times S \to \Delta$, where Δ denotes the set of all the distribution functions F and t is a T-norm [14] so that the following conditions are satisfied ($\mathcal{F}(p,q) = F_{p,q}$ for every $p,q \in S$):

1. $F_{p,q}(x) = 1$, for every $x \in \mathbb{R}^+$ if and only if $p = q$.
2. $F_{p,q}(0) = 0$, for every $p,q \in S$.
3. $F_{p,q} = F_{q,p}$ for every $p,q \in S$ and
4. $F_{p,r}(x+y) \geq t(F_{p,q}(x),F_{q,r}(y))$, for every $p,q,r \in S$ and every $x,y \in \mathbb{R}^+$.

The (ε,λ)-topology is introduced by the (ε,λ)-neighbourhoods of $v \in S$:

$$U_v(\varepsilon,\lambda) = \{u \mid u \in S, F_{u,v}(\varepsilon) > 1-\lambda\},\ \varepsilon > 0,\ \lambda \in (0,1).$$

DEFINITION 4. *Let* $(S,\mathcal{F},t)$ *be a Menger space. A mapping* $W : S \times S \times I \to S$ *is said to be a convex structure if for every* $(u,x,y,\lambda) \in S \times S \times S \times (0,1)$:

$$F_{u,W(x,y,\lambda)}(2\varepsilon) \geq t(F_{u,x}(\tfrac{\varepsilon}{\lambda}),F_{u,y}(\tfrac{\varepsilon}{1-\lambda})),\quad \textit{for every}\quad \varepsilon \in \mathbb{R}^+$$

and $W(x,y,0) = y$, $W(x,y,1) = x$.

It is easy to see that a metric space (S,d) with a convex structure is a Menger space with the same convex structure. It is known that $(S,\mathcal{F},\min)$ is a Menger space, where for every $(u,v) \in X \times X$:

$$F_{u,v}(x) = \begin{cases} 0, & d(u,v) \geq x \\ 1, & d(u,v) < x \end{cases} \qquad \text{for every } x \in \mathbb{R}.$$

Then we can show that a mapping $W : S \times S \times I \to S$, which satisfies the inequality from Definition 1., is a convex structure in the sense of Definition 4. Every random normed space (S,F,t) is a probabilistic metric space with a convex structure defined by:

$$W(x,y,\lambda) = \lambda x + (1-\lambda)y, \text{ for } (x,y,\lambda) \in S \times S \times I, \text{ since}$$

$$F_{u,W(x,y,\lambda)}(2\varepsilon) = F_{u-\lambda x-(1-\lambda)y}(2\varepsilon) = F_{\lambda(u-x)+(1-\lambda)(u-y)}(2\varepsilon) \geq$$

$$\geq t(F_{\lambda(u-x)}(\varepsilon), F_{(1-\lambda)(u-y)}(\varepsilon)) = t(F_{u-x}(\tfrac{\varepsilon}{\lambda}), F_{u-y}(\tfrac{\varepsilon}{1-\lambda}))$$

for every $\lambda \in (0,1)$.

DEFINITION 5. *A Menger space* (S,F,t) *with a convex structure* $W : S \times S \times I \to S$ *satisfies condition* (P II) *if for all* $(x,y,z,\lambda) \in S \times S \times S \times (0,1)$:

$$F_{W(x,z,\lambda),W(y,z,\lambda)}(\lambda\varepsilon) \geq F_{x,y}(\varepsilon), \textit{ for every } \varepsilon \in \mathbb{R}^+ .$$

Every random normed space with the convex structure, which is defined above, satisfies condition (P II) since:

$$F_{\lambda x+(1-\lambda)z-\lambda y-(1-\lambda)z}(\lambda\varepsilon) = F_{\lambda(x-y)}(\lambda\varepsilon) = F_{x-y}(\varepsilon) ,$$

for every $\lambda > 0$.

In [5] the following theorem is proved.

THEOREM B. *Let* (X,F,t) *be a complete Menger space with continuous T-norm* t *and let* S *and* T *be continuous mappings of* X *into* X. *Then* S *and* T *have a common fixed point in* X *if and only if there exists a continuous mapping* $A : X \to SX \cap TX$, *which commutes with* S *and* T *and satisfies the following conditions:*

(i) *For every* $x,y \in X$:

$$F_{Ax,Ay}(\varepsilon) \geq F_{Sx,Ty}(\tfrac{\varepsilon}{q}), \textit{ for every } \varepsilon > 0,$$

where $q \in (0,1)$.

(ii) *There exists* $x_o \in X$ *such that:*

$$\sup_{\varepsilon} \inf_{n \in \mathbb{N}} F_{Ax_n, Ax_o}(\varepsilon) = 1$$

where $\{x_n\}_{n \in \mathbb{N}}$ *is such that* $Ax_{2n-2} = Sx_{2n-1}$ and $Ax_{2n-1} = Tx_{2n}$, $n \in \mathbb{N}$.

Then S,T *and* A *have a unique common fixed point.*

REMARK. Condition (ii) is satisfied if AX is a probabilistic bounded subset of X which means that $\sup_x D_A(x) = 1$ where:

$$D_A(x) = \sup_{t<x} \inf_{p,q \in A} F_{p,q}(t), \quad x \in \mathbb{R}^+.$$

If $S : X \to X$ and (X,F,t) is a Menger space with a convex structure W then S is (W,x_o)-convex $(x_o \in X)$ if, as in Definition 2, $W(Sz,x_o,\lambda) = S(W(z,x_o,\lambda))$, for every $z \in X$, and every $\lambda \in [0,1]$.

THEOREM 2. *Let* (X,F,t) *be a complete Menger space with a convex structure* W *which satisfies condition* (P II),A,S *and* T *continuous mappings from* X *into* X *such that for some* $m \in \mathbb{N}$, $\overline{A^m X}$ *is compact,* AX *be probabilistic bounded,* $AX \subseteq SX \cap TX$ *and for every* $x,y \in X$ *and every* $\varepsilon \in \mathbb{R}^+$:

$$F_{Ax,Ay}(\varepsilon) \geq F_{Sx,Ty}(\varepsilon) .$$

If there exists $x_o \in X$ *so that* S *and* T *are* (W,x_o)*-convex then there exists* $x \in X$ *such that* $x = Sx = Tx = Ax$.

P r o o f. Similarly as in Theorem 1 it follows that there exists, for every $n \in \mathbb{N}$, $x_n \in X$ such that $x_n = A_n x_n = Sx_n = Tx_n$, where $A_n x = W(Ax,x_o,k_n)$ for every $n \in \mathbb{N}$ and every $x \in X$ and $\lim_{n\to\infty} k_n = 1$. Furthermore:

$$F_{x_n,Ax_n}(2\varepsilon) = F_{A_n x_n, Ax_n}(2\varepsilon) = F_{W(Ax_n,x_o k_n),Ax_n}(2\varepsilon) \geq$$

$$\geq t(F_{Ax_n,Ax_n}(\frac{\varepsilon}{k_n}),F_{Ax_n,x_o}(\frac{\varepsilon}{1-k_n})) =$$

$$= t(1,F_{Ax_n,x_o}(\frac{\varepsilon}{1-k_n})) = F_{Ax_n,x_o}(\frac{\varepsilon}{1-k_n}) .$$

Since AX is probabilistic bounded, for every $z \in X$ we have:

$$\inf_{n\in \mathbb{N}} F_{Ax_n,Az}(x) \geq \sup_{t<x} \inf_{p,q\in AX} F_{p,q}(t) = D_{AX}(x) \quad \text{and so:}$$

(4) $$\sup_{x} \inf_{n\in \mathbb{N}} F_{Ax_n,Az}(x) = \sup_{x} D_{AX}(x) = 1$$

Let us prove that $\lim\limits_{n\to\infty} F_{Ax_n,x_o}(\frac{\varepsilon}{1-k_n}) = 1.$

Since $F_{Ax_n,x_o}(\varepsilon) \geq t(F_{Ax_n,Az}(\frac{\varepsilon}{2}),F_{Az,x_o}(\frac{\varepsilon}{2}))$ for every $\varepsilon \in \mathbb{R}^+$ we have that:

(5) $$F_{Ax_n,x_o}(\frac{\varepsilon}{1-k_n}) \geq t(F_{Ax_n,Az}(\frac{\varepsilon}{2(1-k_n)}),F_{Az,x_o}(\frac{\varepsilon}{2(1-k_n)}))$$

for every $n \in \mathbb{N}$. Using the continuity of t, relations (4) and (5) and relation $\lim\limits_{n\to\infty} k_n = 1$, we obtain that $\lim\limits_{n\to\infty} F_{Ax_n,x_o}(\frac{\varepsilon}{1-k_n}) = 1$ and so for every $\varepsilon > 0$, $\lim\limits_{n\to\infty} F_{x_n,Ax_n}(\varepsilon) = 1$. The set $\overline{A^m X}$ is compact and so there exists a subsequence $\{x_{n_k}\}_{k\in \mathbb{N}}$ such that $\lim\limits_{k\to\infty} A^m x_{n_k} = y$

Similarly as in Theorem 1, we can prove that:

$F_{A^k x_n,A^{k+1}x_n}(\varepsilon) \geq F_{x_n,Ax_n}(\varepsilon)$, for every $\varepsilon \in \mathbb{R}^+$, every $n \in \mathbb{N}$ and every $k \in \mathbb{N}$.

Since:

$$F_{x_n,A^m x_n}(\varepsilon) \geq t(F_{x_n,Ax_n}(\frac{\varepsilon}{2}),t(F_{x_n,Ax_n}(\frac{\varepsilon}{2^2}),t(F_{x_n,Ax_n}(\frac{\varepsilon}{2^3}),\ldots,$$

$$,F_{x_n,Ax_n}(\frac{\varepsilon}{2^{m-1}}))\ldots)$$

from relation $t(1,1) = 1$, the continuity of t and:

$$\lim_{n\to\infty} F_{x_n,Ax_n}\left(\frac{\varepsilon}{2^s}\right) = 1, \quad s \in \{1,2,\dots,m-1\}$$

we obtain that:

$$\lim_{n\to\infty} F_{x_n,A^m x_n}(\varepsilon) = 1, \text{ for every } \varepsilon \in \mathbb{R}^+ . \tag{6}$$

The continuity of t, relation (6) and the inequality:

$$F_{x_{n_k},y}(\varepsilon) \geq t(F_{x_{n_k},A^m x_{n_k}}(\tfrac{\varepsilon}{2}), F_{y,A^m x_{n_k}}(\tfrac{\varepsilon}{2}))$$

imply that $\lim_{k\to\infty} x_{n_k} = y$. Since A is continuous from the inequality:

$$F_{y,Ay}(\varepsilon) \geq t(F_{y,x_{n_k}}(\tfrac{\varepsilon}{2}), t(F_{x_{n_k},Ax_{n_k}}(\tfrac{\varepsilon}{4}), F_{Ax_{n_k},Ay}(\tfrac{\varepsilon}{4})))$$

it follows that $F_{y,Ay}(\varepsilon) = 1$, for every $\varepsilon \in \mathbb{R}^+$ and so $y = Ay$. Since S and T are continuous, from $x_{n_k} = Sx_{n_k} = Tx_{n_k}$, $k \in \mathbb{N}$ we obtain that $y = Ay = Sy = Ty$.

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Received by the editors August 7, 1984.

REZIME

O ZAJEDNIČKIM NEPOKRETNIM TAČKAMA U METRIČKIM I VEROVATNOSNIM METRIČKIM PROSTORIMA SA KONVEKSNOM STRUKTUROM

U ovom radu dokazana su neka uopštenja Teorema 1 i 2 iz [5] u metričkim i verovatnosnim metričkim prostorima sa konveksnom strukturom.